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EFFECT OF POST-ORE DIKE INTRUSION ON BUTTE ORE MINERALS.[1]

RENO H. SALES AND CHARLES MEYER.

ABSTRACT.

Post-ore rhyolitic to dacitic dikes up to one hundred feet wide cut the ore-bearing veins in the Butte district. Pyrite-bearing chalcocite ore, typical of Butte's Central Zone, is converted to massive bornite and chalcopyrite adjacent to the dikes. The reaction is interpreted as a duplication in nature of laboratory furnace experiments in which similar products were obtained by heating chalcocite and pyrite together in the absence of excess sulphur.

The textural patterns evolved between chalcopyrite and bornite adjacent to the dikes, and between bornite and chalcocite in the lower intensity metamorphosed zone farther from the dikes, must all have resulted through exsolution in the solid state, with possible minor readjustments owing to inversions and recrystallization during the declining thermal history after exsolution.

INTRODUCTION.

FOR some time the Anaconda Company has had a project involving application of modern geological laboratory methods to the problem of ore finding. One of the laboratory's chief assignments has been to establish a theory of ore genesis to serve as a basis for current and future exploration in the Butte district.

In previous papers we have proposed for Butte two coordinated hypotheses: first, contemporaneity of sericitization and argillization in wall rock alteration,[2] and second, critical control of the zonal distribution of copper-iron-sulphur series minerals by progessive changes in concentration of sulphur in the hydrothermal solution.[3] Those two hypotheses are the basic elements of the theory used to interpret mineral zoning in the Butte district.

[1] Presented before a joint meeting of the American Institute of Mining and Metallurgical Engineers, Mining Geology Division, and the Society of Economic Geologists, St. Louis meeting, February 1951.

[2] Sales, Reno H., and Meyer, Charles, Wall rock alteration at Butte, Montana: Am. Inst. Min. Met. Eng. Trans., vol. 178, pp. 9–35, 1948. Sales, Reno H., and Meyer, Charles, Interpretation of wall rock alteration at Butte, Montana: Colorado School of Mines Quart., vol. 45, no. 1b, pp. 261–273, 1950.

[3] Sales, Reno H., and Meyer, Charles, Results from preliminary studies of vein formation at Butte, Montana: ECON. GEOL., vol. 44, pp. 465–484, 1949.

According to the sulphur control hypothesis, as long as the sulphide ion concentration of a given increment of hydrotheraml solution remained high, deposition from it of pyrite and a copper sulphide solid solution low in iron was favored. That was true, for example, as long as the solution moved in channels within Butte's Central Zone where all iron in wall rock minerals already had been sulphidized by the hydrothermal process. However, as that increment of hydrothermal fluid migrated toward the periphery of the deposit outside the Central Zone, wall rock iron derived from altering biotite and hornblende used up part of the sulphur content of the invading solution to form the disseminated pyrite at the advancing front of sericitization. Thus the ratio of sulphur to sulphide-forming metal ions in the solution decreased, and the combined copper-iron sulphide minerals bornite and chalcopyrite tended to be favored in resulting Intermediate Zone copper ore bodies. That preferred mineralogical distribution is found even though the copper-iron ratio in chalcopyrite-bornite rich vein aggregates is the same as that of the chalcocite-pyrite ore within the Central Zone.

Experimental evidence has been published [4] showing that a copper-rich sulphide solid solution is stable in contact with pyrite even at a high temperature, provided abundant excess sulphur is available. A polished section containing pyrite grains embedded in chalcocite was heated at 300° C for three days in an atmosphere of hydrogen sulphide. When cooled and repolished at the end of that period the section showed no chalcopyrite or bornite at the margins of the pyrite grains even under high magnification. Similar heating with the sample immersed in sodium sulphide or elemental sulphur produced the same qualitative results. However, when the same specimen was reheated in air, CO_2, steam or any other low-sulphur environment, it lost sulphur, and chalcopyrite was formed by reaction between the pyrite and the surrounding copper-rich copper sulphide solid solution. The chalcopyrite penetrated the pyrite, leaving residuals of pyrite in a network of chalcopyrite veinlets. A pinkish halo which developed around the chalcopyrite proved to be an iron-bearing solid solution grading out into iron-free copper sulphide. It is possible to exsolve an impure bornite from the pink halo, verifying the experience of Schwartz [5] and others.

In past decades numerous writers have attached critical significance to the fact that the textural patterns thus derived experimentally do not often resemble the patterns observed between chalcocite and bornite in most natural ores, including those at Butte. The lack of resemblance was offered as negative evidence to support the proposition that exsolution was not quantitatively important in the development of most textural patterns between bornite and chalcocite in natural ores. Two alternative propositions were considered strengthened by that negative conclusion: (1) simultaneous deposition of bornite and chalcocite as independent minerals in contact with each other, or (2) incomplete replacement of bornite by chalcocite, effected through introduction of copper ions in a late hypogene or supergene enrichment process. Both

[4] Idem., p. 479, 1949.

[5] Schwartz, G. M., Experiments bearing on bornite-chalcocite intergrowths: ECON. GEOL., vol. 23, pp. 381–397, 1928.

alternatives require a low temperature environment for the introduction of an important part of the copper in bornite-bearing chalcocite-rich ore bodies, because bornite and chalcocite are not stable in contact with each other much above 150° C at any pressures likely to develop during ore deposition. A low-temperature, relatively copper-rich solution was thus generally predicated as a closing phase of hypogene activity in chalcocite-bearing ore bodies, or, alternatively, such ore bodies were believed to be supergene in origin. Thus it is obvious that interpretations of bornite-chalcocite textures have exerted a substantial influence on the growth of the general theory of hypogene copper sulphide deposition.

In previous papers the present writers have contended that extensive field evidence supports neither low temperature nor significantly changing

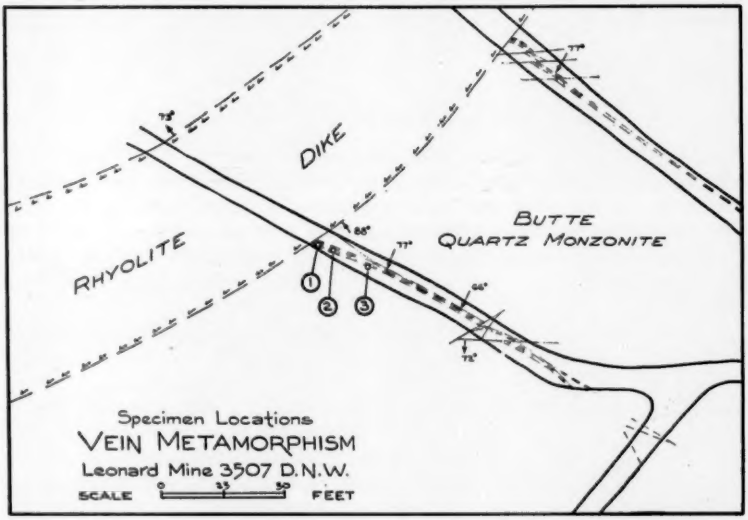

FIG. 1. Sketch of 3507–DNW, Leonard Mine, showing a vein (dashed) cut by a rhyolite dike. The encircled numbers are specimen locations referred to in the text.

copper-iron ratio in the depositional environment of the chalcocite ores at Butte. Therefore, it was postulated that even the more irregular bornite-chalcocite textures, whose microscopical geometric configurations are so suggestive of tattered bornite residuals undergoing replacement by chalcocite, must be the result of some process of exsolution from a solid solution of the chemical components of both minerals, which had been deposited originally under high intensity conditions.

The purpose of the present paper is to introduce new evidence bearing on the genetic interpretation of the field distribution and textural relations of the copper-iron-sulphur series minerals at Butte. This new evidence is derived

from study of spectacularly metamorphosed contact zones in chalcocite-rich Butte veins where those veins are intruded by post-ore rhyolitic to dacitic dikes. The dikes, which range up to 100 feet in thickness, heated the copper ores sufficiently to induce in them all the reaction between pyrite and chalcocite that have been generated experimentally. After the intrusion the products of the reactions must have cooled slowly to their present temperature of about 50° C. The cooling rate was undoubtedly faster than that which prevailed after ore deposition itself, but probably much slower than is practicable in laboratory experiments. Also, after complete dissipation of the heat of the dike, the sulphide mineral reaction products have had a geologically substantial period of time, at a temperature of 50° C or higher, to enable them to accomplish more complete internal reordering. Throughout the period following dike emplacement, recurrent tectonic stresses may also have contributed to readjustment of internal structures and inter-mineral contacts through plastic flow.

THERMAL METAMORPHISM OF THE COPPER MINERALS.

The effects of a post-ore dike upon the mineralogy of a copper vein were first seen on the deep levels of the West Colusa mine, where several northwest striking veins are intersected almost at right angles by the dike. The mine geologist's notes, taken as the drifts were being driven to points of intersection with the dike, show that bornite and chalcopyrite began to appear in these typical Central Zone chalcocite-pyrite-enargite veins as the dike was approached.

Subsequently in the Belmont mine a detached ore fragment composed of chalcopyrite, bornite and quartz was found imbedded in the dike rock. Apparently it had been torn from a vein, perhaps at a deeper horizon. There were early suggestions that this block of drag was a demonstration that at greater depth the chalcocite-pyrite ore would change to chalcopyrite-bornite ore. This important possibility aroused much local interest, and finally brought about a careful field and laboratory investigation of the effect of post-

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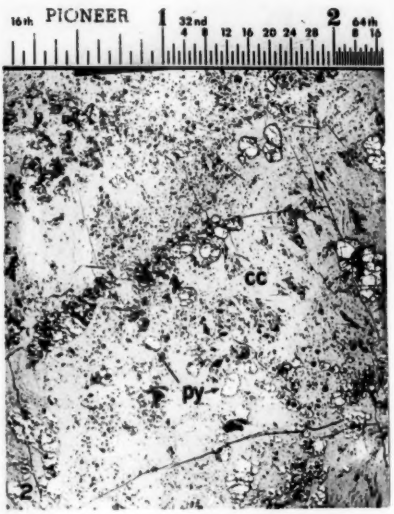
FIG. 2. Polished hand specimen of chalcocite-pyrite ore taken at location No. 3, Figure 1. The disseminated bornite is not visible in the hand specimen. Enargite (En) is more abundant in other portions of the vein.

FIG. 3. Photomicrograph showing disseminated bornite in chalcocite, with enargite and pyrite. The proportion of bornite is a little higher than average in this specimen, perhaps because of its location (3—Fig. 1) at the outer edge of contact metamorphism. See also Figure 1, etc., in the reference of footnote No. 3. Vert. refl. light, × 130.

FIG. 4. Polished hand specimen of metamorphosed vein adjacent to the dike. Note the dike stringer in the lower part of the photograph. Chalcopyrite is clustered around pyrite residuals. Pyrite appears dark because it is unpolished. No chalcocite remains in this field. Tennantite (tn) locally contains a few small enargite residuals.

FIG. 5. Photomicrograph of chalcopyrite-bornite grating texture in metamorphosed ore rich in chalcopyrite Note transition to more irregular "island" bornite near right-center of picture. Vert. refl. light, × 55.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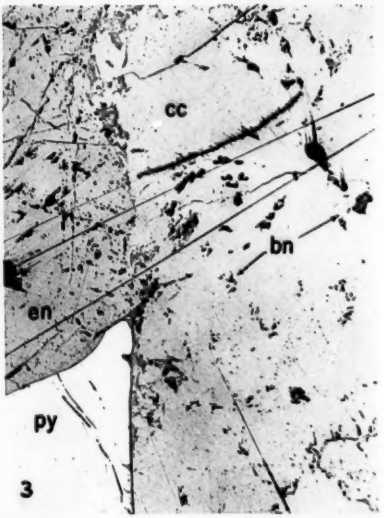
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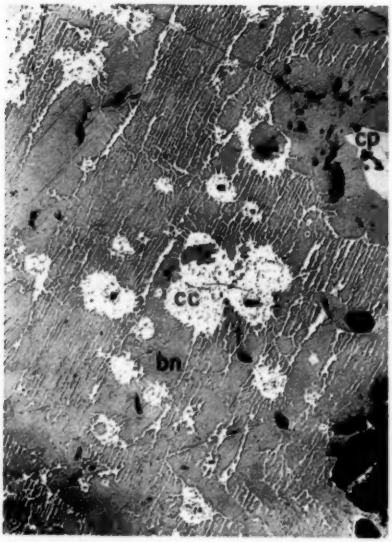
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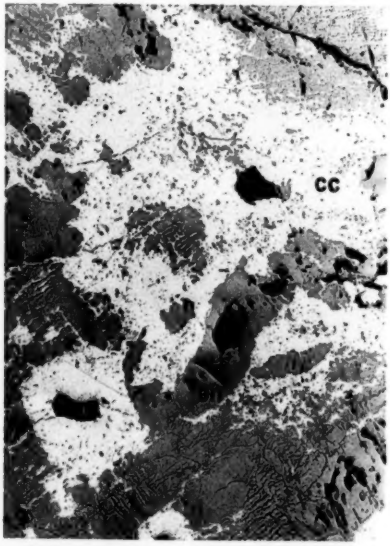
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mineral dikes upon copper mineralogy in intruded veins. Fortunately, after the study was under way an unusually good transection of a copper vein by a dike was disclosed in a drift being driven on the 3,500 level of the Leonard Mine. Here it was possible to examine the mineralogical change foot by foot along strike, and to select systematic samples for detailed study.

As described in earlier papers on Butte sulphides, chalcocite and enargite make up 95 percent or more of the total copper-bearing sulphide content of normal Central Zone ore (Figs. 2 and 3). Pyrite, of course, is the abundant and ubiquitous associate of the copper minerals. In such Central Zone ore, bornite is scarce except as microscopic disseminations in the chalcocite, and chalcopyrite is exceedingly rare. The specimen shown in Figure 3 was collected at location No. 3, Figure 1, on a plan of a part of the 3,500 level of the Leonard Mine, deep in the Central Zone. Toward the Northwest, 23 feet away, a big East-West dike transects the vein at a high angle. Broken fragments of vein material are present in the wall of the dike, and a narrow split of the dike may be seen in immediate contact with the suphide minerals in Figure 4. The fragments, together with the ore still in place in the vein up to a distance of 4 feet from the dike, have been intensely metamorphosed. They are changed from the pyrite- and enargite-bearing chalcocite seen in previous photographs to massive chalcopyrite and bornite studded with tennantite.

In the intensely metamorphosed zone the relative proportions of chalcopyrite and bornite depend upon the amount of pyrite originally present with the chalcocite as well as on the proximity of the dike. Massive chalcopyrite is often bunched close to clusters of pyrite residuals (Fig. 4). When chalcopyrite exceeds bornite, the bornite is often held in a grid pattern within the chalcopyrite (Fig. 5). But where the proportion of the two minerals is reversed, islands of chalcopyrite are generally held in a uniform field of bornite (Fig. 6). Sometimes veinlet-like masses of bornite penetrate the chalcopyrite islands, and in other cases spicule-lined veinlets of chalcopyrite penetrate the

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FIG. 6. Chalcopyrite "islands" in bornite. Note the gash-like "veinlets" of bornite in the chalcopyrite "islands." Vert. refl. light, × 55.

FIG. 7. Scattered chalcopyrite "islands" in bornite carrying a crude lattice and vermicular aggregates of finely dispersed chalcocite. Note absence of chalcocite from bornite immediately surrounding chalcopyrite "islands." Vert. refl. light, × 65.

FIG. 8. Chalcocite lattice in bornite, plus chalcocite "pods." The chalcocite "pods" contain finely disseminated bornite. Rather large and somewhat irregular bornite "spines" are prominent. One grain of chalcopyrite, with its usual chalcocite-free bornite rim, is partly visible on the right edge of the photograph. Vert. refl. light, × 65.

FIG. 9. Bornite-chalcocite field near outer edge of metamorphic effect. Large bornite spines are distorted. Chalcocite contains irregular particles of disseminated bornite, similar to the texture of normal Butte chalcocite ore. The general appearance of the field suggests progressive replacement of bornite by invasion of chalcocite. Yet the bornite present here was formed as a result of thermal metamorphism of a pyrite-bearing chalcocite ore. Vert. refl. light, × 65.

bornite field. Both the grating texture and the "island-and-sea" pattern have their counterparts in experimental exsolution of the two minerals by Schwartz.[6]

A few rounded islands of tennantite are present in either chalcopyrite or bornite. The tennantite usually contains numerous tiny rounded blebs of chalcopyrite or bornite. It is significant that the tennantite, chalcopyrite and bornite found in the metamorphosed zone with no chalcocite or with only subordinate chalcocite are also common associates in normal copper ore at and near the periphery of copper mineralization at Butte. But they are foreigners to the Central Zone except adjacent to the dike.

Locally the Butte chalcocite contains appreciable quantities of silver in solid solution. Where such silver-bearing chalcocite is metamorphosed adjacent to the dike, the silver is no longer soluble and it is "sweated out." Wire silver is present in tiny carbonate-bearing vugs in the resulting chalcopyrite-bornite ore.

There can be little doubt that the bornite, chalcopyrite and tennantite in these occurrences are the metamorphosed products of reactions generated by the heat of the dike intrusion; the chalcopyrite and bornite by reaction of pyrite and chalcocite, and the tennantite from enargite. The metamorphism must have taken place sufficiently long after deposition of the ore that hydrothermal heat and "excess" sulphur were low. And sulphur must have been driven off during the reaction because mixtures of pyrite and chalcocite have higher sulphur content than mixtures of chalcopyrite and bornite having the same copper-iron ratio. Verification of the expurgation of sulphur is also furnished by the local complete desulphidation of pyrite where copper-free pyrite veinlets are cut by the dike. The pyrite is baked all the way to hematite. Most of the sulphur was driven out of the system laterally and upward, but part was evidently recompounded on the way out. Evidence for such movement of sulphur by the dike is furnished by an exposure in the Peripheral Zone where a manganese carbonate vein is cut by a North-South trending member of the dike system. In a zone several tens of feet wide adjacent to the dike, the rhodochrosite of the vein is partially converted to the manganese sulphide, alabandite. The alabandite occurs in small granules which are sometimes aligned along the original cleavage of the carbonate.

A little of the liberated sulphur was evidently also held in solid solution in the chalcopyrite-bornite reaction products during the metamorphic period. It separated out during subsequent cooling to unite with extra copper and form the little patches and discontinuous grain boundary veinlets of covellite and minor blue chalcocite which are found here and there in the matrix bornite. An interesting sidelight is that cavities resembling shrinkage cracks are present in these pods of blue chalcocite embedded in bornite and chalcopyrite which have themselves been generated by reaction in the solid state between earlier chalcocite and pyrite at deep mine levels. It seems quite unnecessary to sup-

[6] Schwartz, G. M., Intergrowths of bornite and chalcopyrite: ECON. GEOL., vol. 26, pp. 186–201, 1931.

pose that late, externally applied copper ion pressure induced this apparent "centrifugal replacement." More likely the ingredients were exsolved from the bornite as it reached its ordered state during the cooling process.

All of the chalcopyrite-bornite fields shown in Figures 4 to 6 were taken from the zone within 4 feet of the dike in the 3,500 Leonard Mine drift shown in Figure 1. At a distance of 5 to 7 feet from the dike, where the reaction was less intense, chalcopyrite islands are less numerous, and a small amount of gray chalcocite is present in the bornite field. No covellite is associated with this chalcocite, and most of the chalcocite itself seems to be free from excess sulphur. It gives a good low-chalcocite X-ray powder pattern, and sealed samples show reversible inversion at approximately the 105° C inversion temperature in a Buerger heated powder camera. Evidently the time interval during and after its exsolution enabled this chalcocite to reach its present stage of lattice equilibrium even though it must have started from a metastable copper-rich exsolution product similar to that obtained during experimental work on bornite-chalcocite mixtures. If final ordering to chalcocite can take place during the post-dike period in the metamorphosed zone, it certainly can take place during the longer time interval following initial deposition of a similar solid solution by the hydrothermal process itself.

In Figure 7 a loose chalcocite grating may be seen in bornite except in the areas immediately surrounding chalcopyrite islands. The proportion of this chalcocite increases going away from the dike, as shown in Figure 8. Here the chalcocite grid is interrupted by a few pure bornite masses which have the unmistakable spindle-shaped outline of bornite spines. The shape and orientation pattern of the spines resemble those produced by experimental exsolution, though the spines in Figure 8 are much larger and more irregular in outline than any experimental growths which have been figured in the literature. The larger size is expectable; they had a longer time to grow.

Particular attention should be called to the irregularities of outline, for the marginal embayments and veining by chalcocite geometrically suggest partial replacement of the bornite by the chalcocite. Still farther from the dike (Location 2, Fig. 1) the suggestion of replacement is further strengthened (Fig. 9). Here in a chalcocite-rich area surrounded by bornite, disseminated bornite appears in the same pattern so abundantly distributed throughout the immense chalcocite ore bodies in Butte's Central Zone. Yet those irregular bornite fragments are present in a field showing bornite spines, and in this metamorphosed zone all the bornite now present was formed in the solid state by exsolution. The bornite here must have exsolved from an iron-bearing copper sulphide solid solution formed by thermally induced chemical combination of original earlier chalcocite and iron from nearby pyrite. Most of the bornite here is the later mineral, insofar as its chemical identity is concerned. Furthermore, the original hydrothermally deposited chemical ingredients, copper, iron and sulphur, for both the bornite and the chalcocite were all present in the vein as crystalline solids (chalcocite and pyrite) long before the generation of any of the currently observed textures.

CONCLUSIONS.

The contact metamorphism of copper ores in Butte's Central Zone offers corroborative evidence for several of the suggestions already advanced concerning interpretation of field distribution patterns and textural interrelationships of the copper minerals.

(1) All the textures geometrically suggestive of replacement of bornite by chalcocite can be generated in the solid state by exsolution and minor subsequent recrystallization without necessary addition of copper or removal of iron. Therefore, the hydrothermal solution need not be progressively richer in copper during the late stages of hypogene copper introduction.

(2) Furthermore, since the *mineral* chalcocite is not required to have been deposited by the hydrothermal solution in contact with bornite, neither was there necessarily a low temperature environment for late-stage copper deposition. That conclusion removes a serious objection to the hypothesis of rising thermal as well as chemical intensity at a specific reference point during active copper deposition in a vein.

(3) Thus critical control of copper mineralogy by progressively changing sulphide ion concentration has increasing appeal as the explanation for the observed distribution of copper-iron-sulphur series minerals at Butte. The core of chalcocite-pyrite ores is within the zones of high intensity sericitization and pyritization, and bornite and chalcopyrite, with proportionately less chalcocite, are prevalent at the outer edges of copper deposition, where much unsulphidized iron remains in the rock alteration zones between veins.

The evidence from the dike metamorphism emphasizes the delicacy of the interpretative step between observation of the mineralogical character and space patterns of a given ore mineral assemblage and application of those observations to a hypothesis for original emplacement of the economically valuable constituents of the ore. It is not difficult to imagine how different the copper zone at Butte would look if the whole deposit had been subjected to post-hydrothermal metamorphism, even if that action were no greater in intensity than the rather gentle thermal treatment accorded the Butte veins where they were cut by the dikes.

ANACONDA COPPER MINING CO.,
BUTTE, MONTANA,
Oct. 2, 1951.

THE SOLUBILITY OF SOME MINERALS IN SUPERHEATED STEAM AT HIGH PRESSURES.

GEORGE W. MOREY AND JAMES M. HESSELGESSER.

ABSTRACT.

The solubility of salts and minerals in superheated steam at high pressures is of importance to geologists in their attempts to interpret and explain the genesis of pneumatolytic and vein deposits, and the experimental demonstration and measurement of such solubilities is of interest to them. The present paper describes an apparatus and a method which have been used for this purpose at temperatures up to 600° C and at pressures up to 2,000 bars.

APPARATUS AND METHOD.

THE method used was to pass steam at constant pressure over the mineral, crushed to pass a screen of 4 meshes per inch and be retained on one of 8 meshes per inch, contained in a heated bomb, and to weigh and analyze the condensed steam. The apparatus is shown in diagrammatic form in Figure 1. Water is pumped into the pressure line, which includes a reservoir, volume 2240 cc, a pressure gauge calibrated against a dead-weight gauge, a pressure controller, the bomb, and a throttling valve. The earlier form of the pressure controller described in a preceding paper [1] was a Bourdon gauge which maintained constant pressure by means of a light and photocell. In the later work a Baldwin Fluid Pressure cell, the sensitive elements of which are two Baldwin Strain Gauges, was used in conjunction with a special Brown Electronic Potentiometer. The instrument has a pressure range up to 3,300 bars and a high sensitivity.

The bomb is shown in Figure 2. It is of Inconel X, which has proved more satisfactory than stainless steel in this and other work at high temperature and pressure. The diameter of the bomb is 2.5 inches, of the chamber, ⅞ inches. The over-all length is 11 inches; the chamber is 7.5 inches long. The modified Bridgman-type closure makes use of the internal pressure to maintain the seal. The plunger is drilled with a ⅛-inch hole, and the head of the plunger fits inside the chamber of the bomb. A follower washer, held in place by the cap, fits over the stem of the plunger, and the lower ⅛ inch fits inside the chamber of the bomb. A silver washer, ⅛ inch thick, fits over the stem of the plunger and is compressed between the head of the plunger and the follower. The initial closure is made by screwing down the nut bearing on the top of the cap; the final closure, by the action of the pressure in the interior

[1] Morey, G. W., and Hesselgesser, J. M., The solubility of quartz and some other substances in superheated steam at high pressures: Am. Soc. Engrs. Trans., vol. 73, pp. 865–875, 1951. All of the work described in that paper, and much in this one, is due to the interest and financial support of Hall Laboratories, Inc., Pittsburgh, Pennsylvania.

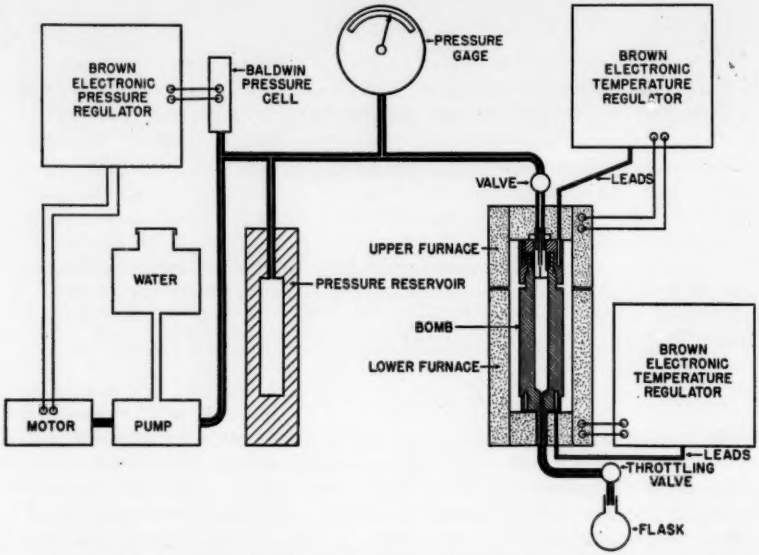

FIG. 1. Diagrammatic outline of pressure apparatus. Distilled water is pumped into the pressure line, which includes a reservoir, a reading gauge, and a regulator to maintain the pressure constant. The solid material is contained in the bomb and heated in the regulated electric furnace. The water is changed to steam, passes over the solid and out of the bomb, constant pressure being maintained on the cooled water until the throttle valve is reached. The condensed water is collected, weighed, and analyzed.

of the bomb. The area of the head of the plunger is 0.60 square inch, that of the silver washer, 0.30 square inch, so that the pressure on the washer is twice the internal pressure. This closure has never leaked, even when subjected to wide changes in pressure and temperature.

The furnace has two windings, each of which is controlled by a Brown Electronic Controller, using chromel-alumel thermocouples. The main winding is controlled by a thermocouple inserted in the main part of the bomb. This is the exit side. The secondary winding is controlled by a couple in the

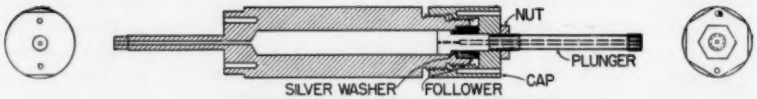

FIG. 2. The pressure vessel. The pressure vessel consists of a bomb, a cap, and a plunger. The bomb is 2.5 inches outside diameter with a chamber, 0.875-inch bore and 9 inches deep. The cap screws on and holds the plunger in place. The closure is made by the plunger; the initial compression of the plunger is by the nut on the threaded part of the bomb.

cap; this is the entrance side, and the required heat input changes with the rate of flow of the water. Temperature is measured by platinum-platinum 10 percent rhodium couples similarly placed in wells in the body and cap, and the two temperatures are maintained the same within ± 2° C.

The bomb is fastened to the pressure line by a standard cone coupling. The water passes into the hot bomb as steam, over the mineral, out of the bottom of the bomb, and through a cooling tube consisting of 2 feet of 1/16-inch bore pressure tubing to the throttling valve. Here the flow is adjusted to the desired rate, usually between 10 and 25 drops per minute, and the water is collected in a weighed flask. At the end of the run the condensed water is weighed and analyzed. No indication of deposition of material in the exit line was observed in the experiments described in this paper.

EXPERIMENTAL RESULTS.

Quartz.

Much work on quartz was described in the previous paper, and details of these runs are not given here. After the earlier paper had been preprinted and presented orally, a paper by Kennedy [2] which covered much of the same ground appeared in this journal. His discussion of previous work was adequate so such discussion will be omitted here; his experimental results are commented on below.

The quartz used was crushed to pass a screen of 4 meshes per inch and be retained on one of 8 meshes. It was then digested with dilute aqua regia for a few days and washed. Table 1 gives details of the new experiments; similar details for other pressures and temperatures are given in the previous publication. The columns give for each run the weight of condensate, the length of time taken for the run, the rate of flow in grams water per minute, the weight silica found, and the weight percent silica found in that run. Comparison between runs gives an idea of the agreement between experiments. The average is obtained by dividing the total weight of silica by the total weight of condensate.

The final values of these runs have been combined in Table 2 with those of the previous paper, and in the same table are given those results by Kennedy [3] which were obtained under comparable conditions of temperature and pressure. The agreement is in general good, in some cases excellent. When the difference in method is considered, the correspondence between the two sets of results makes it probable that the solubility results are true equilibrium values.

Our results in Table 2 are shown in Figure 3. Each of the curves in Figure 3 for 400°, 500°, and 600° C shows an upward curvature at the higher pressures, indicating a falling off in the rate of increase in solubility with pressure, and at the higher pressures the rate of increase in solubility increases with the temperature. At 400° C the solubility curve is becoming very steep

[2] Kennedy, George C., A portion of the system silica—water: ECON. GEOL., vol. 45, pp. 629–653, 1950.

[3] Dr. Kennedy has kindly checked the interpolations necessary for making this comparison.

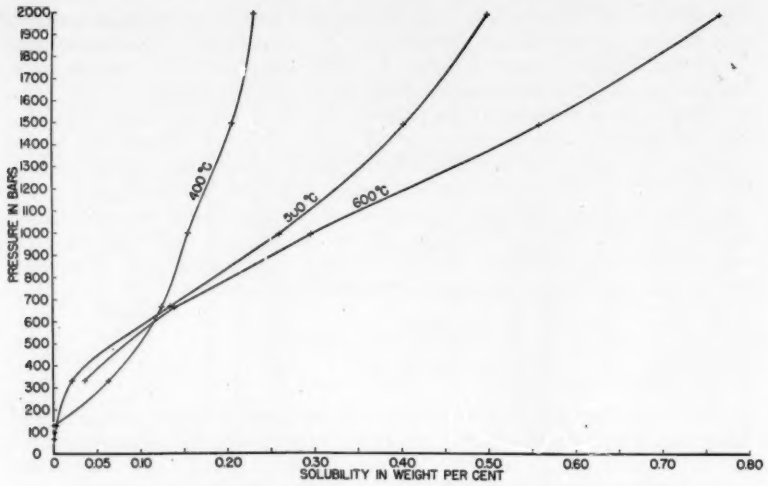

FIG. 3. The solubility results for quartz at 400°, 500°, and 600° C, expressed as weight percent SiO_2 in the condensate.

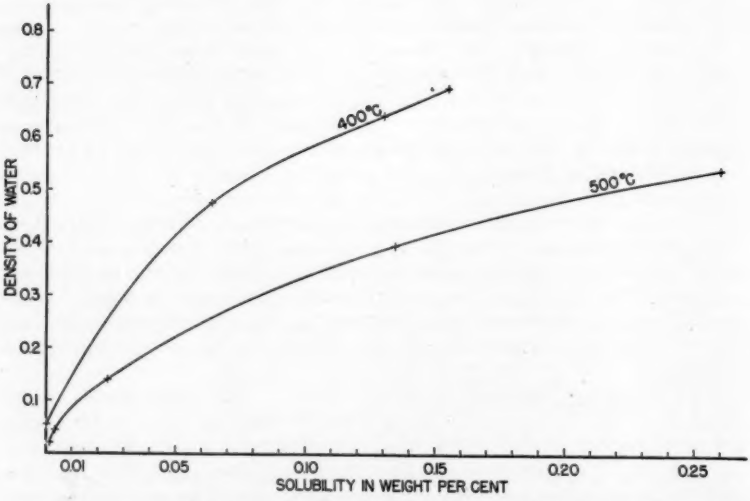

FIG. 4. The solubility results for quartz at 400° and 500° C, up to 1,000 bars, plotted as weight percent SiO_2 in the condensate against the density of water at the given temperature and pressure.

and a further increase in pressure probably would not greatly increase the silica content of the gas, but at 500°, and especially at 600° C, further increase in pressure would result in greater solubilities. At lower pressures the curves for 400° and 500° C cross at two places. At two different pressures the solubility is the same at 400° C as at 500° C; between these pressures the solubility is greater at 400° than at 500°, and above and below these pressures it is greater at 500° than at 400°. The surface representing the solubility at different pressures and temperatures evidently has a double curvature, and it does not necessarily follow that the solubility would be the same at an intermediate temperature. These peculiar relationships are caused in large part by

TABLE 1.

SOLUBILITY OF QUARTZ IN SUPERHEATED STEAM.

Weight condensate in grams	Duration minutes	Rate grams per minute	SiO_2 grams	Weight percent SiO_2
400° C, 1,500 bars (22,500 psi)				
384	240	1.60	0.8315	0.2165
630	480	1.31	1.1416	0.1812
241	300	0.80	0.5344	0.2217
600	645	0.93	1.2911	0.2152
886	1500	0.59	1.8616	0.2101
Total 2741			5.6602	0.207
400° C, 2,000 bars (30,000 psi)				
549	210	2.61	1.2804	0.2332
643	275	2.34	1.4738	0.2292
474	540	0.88	1.0947	0.2310
745	480	1.55	1.8383	0.2468
418			0.8943	0.2134
Total 2829			6.5815	0.233
500° C, 1,500 bars (22,500 psi)				
586	510	1.15	2.3512	0.4012
476	886	0.54	1.9281	0.4051
526	540	0.97	2.1339	0.4057
512	840	0.61	2.1043	0.4110
870	600	1.45	3.4699	0.3988
Total 2970			11.9874	0.404
500° C, 2,000 bars (30,000 psi)				
577	420	1.37	2.8974	0.5022
118	120	1.00	0.5901	0.5000
594	360	1.65	2.9482	0.4963
583	480	1.21	2.8973	0.4970
Total 1872			9.330	0.499

TABLE I—(*Continued*).

Weight condensate in grams	Duration minutes	Rate grams per minute	SiO_2 grams	Weight percent SiO_2
		600° C, 333 bars (5,000 psi)		
374	375	1.00	0.1264	0.0341
565	945	0.60	0.2071	0.0367
367	525	0.70	0.1318	0.0359
508	360	0.41	0.1915	0.0377
Total 1814			0.6568	0.036
		600° C, 1,000 bars (15,000 psi)		
680	330	2.07	1.8466	0.2718
511	1440	0.36	1.3769	0.2695
1131	1620	0.70	3.5165	0.3109
280	720	0.39	0.8668	0.3096
622	480	1.30	1.8448	0.2966
1276	945	1.35	3.8652	0.3029
Total 4500			13.3168	0.296
		600° C, 1,500 bars (22,500 psi)		
421	270	1.56	2.3920	0.5682
715	290	2.47	3.9973	0.5591
318	260	1.22	1.7088	0.5374
502	240	2.09	2.8255	0.5628
Total 1956			10.9234	0.559
		600° C, 200 bars (30,000 psi)		
279	135	2.07	2.0865	0.7479
519	210	2.47	3.7285	0.7184
428	360	1.19	3.4300	0.8014
462	180	2.56	3.6610	0.7924
Total 1688			12.9060	0.765

the pressure-volume relationships of steam at high pressure and temperature, and, in particular, by the proximity of 400° C to the critical point of water, 374.11° C and 221.06 bars. This is indicated in Figure 4, in which the solubilities at 400° and 500° up to 1,000 bars are plotted against, not pressure as in Figure 3, but the density of water at the given temperature and pressure. The curves no longer cross, and the solubility is higher at 500° than at 400° C. It is evident that solubility is determined primarily not by pressure but by the amount of water present.

Experiments were also made with SiO_2 glass, with results summarized in Table 3. Much larger values for solubility were found with silica glass than with quartz, but in every case when the run was continued for several days the glass crystallized to quartz, and the solubility dropped to that of quartz at

the given temperature and pressure. It is realized that these results cannot represent a true solubility. Glass is an amorphous phase. The criterion for a reversible solubility is usually taken to be that if a change in conditions, e.g., an increase in pressure, causes a material to dissolve, the opposite change, a decrease in pressure, should cause it to separate in the same thermodynamic

TABLE 2.

SUMMARY OF SOLUBILITY RESULTS WITH QUARTZ.

Pressure bars	Solubility weight percent SiO_2	Partial pressure SiO_2 bars	Kennedy
		300° C	
333–1000	0.062		0.068–092
		360° C	
333	0.085		0.097
		400° C	
33	0.0001	—	—
67	0.0003	0.2×10^{-3}	—
133	0.0005	0.7×10^{-3}	—
333	0.064	0.21	0.060
667	0.126	0.84	0.142
1000	0.155	1.55	0.173
1500	0.206	3.1	0.217
2000	0.231	4.6	—
		500° C	
33			
67	0.0014	0.91×10^{-3}	—
133	0.0036	3.3×10^{-3}	—
333	0.022	0.07	
667	0.135	0.9	0.132
1000	0.260	2.6	0.232
1500	0.404	6.1	—
2000	0.499	10.0	—
		600° C	
333	0.036	0.12	—
1000	0.296	3.0	—
1500	0.559	8.4	—
2000	0.765	15.3	—

conditions as before. This does not happen, and when a phase does separate it is quartz, not silica glass. The solubility values and values obtained with any amorphous silica represent rates of solution under fairly well defined conditions. Constant values may be obtained under different conditions, but different values may be obtained with amorphous silicas of different histories.

In Table 2 are given partial pressures of SiO_2 in the steam. These were obtained by multiplying the total pressure in bars by the weight fraction SiO_2 and are not intended to convey any implication as to the molecular condition of SiO_2 in the steam, which will remain a matter of speculation until some method of molecular weight determination under these somewhat extreme conditions is devised. Nothing is known about the extent of association of water vapor itself at high temperature and pressure. As for the SiO_2, it is improbable that it exists as SiO_2 molecules. In all possibility it exists in tetrahedral coordination as silicic acid or as a hydrated silicic acid, but speculations are incapable at present of experimental test.

In a number of cases the silica content of the condensed steam was determined by a colorimetric method, which is supposed to differentiate between

TABLE 3.

SUMMARY OF SOLUBILITY RUNS WITH SILICA GLASS.

Pressure bars	Pressure psi	Solubility Grams SiO_2 per million grams H_2O	
		Opaque glass	Quartz
	400° C		
133	2,000	0.004	0.0005
333	5,000	0.138	0.064
667	10,000	0.243	0.126
	500° C		
333	5,000	0.035	0.022
667	10,000	0.254	0.135
1000	15,000	0.418	0.260

crystalloidal and colloidal silica.[4] The agreement between gravimetric and colorimetric results was good, and none of the silica appeared to be in colloidal solution.

Albite.

The Amelia County, Virginia, albite used was from the Laboratory stock, an analysis of which was given by Day and Allen.[5] It was feared that some alumina might separate from the steam in the cooling tube and an auxiliary bomb was placed in air next to the main bomb on the exit side. Its temperature was usually about 250° C; the actual temperature depended upon that of the main bomb and upon the rate of flow. The auxiliary bomb was of the type commonly used in this Laboratory, 18 cc capacity, but had a hole drilled in the bottom to connect with the tubing leading to the needle valve. A tall platinum

[4] We thank Hall Laboratories, Inc., and the Philadelphia Quartz Company for making these determinations.

[5] Day, A. L., and Allen, E. T., The isomorphism and thermal properties of the feldspars: Part 1, Thermal study. Carnegie Inst. of Washington, 1905.

crucible was placed in the auxiliary bomb, so arranged that the hot condensed water flowed into the crucible, over the top, and then out the bottom of the bomb. After the series of runs this bomb and crucible were washed out and the washings analyzed. The results are indicated by "Extra" in Table 4 and added to the totals in making up the average.

TABLE 4.

SOLUBILITY OF ALBITE IN SUPERHEATED STEAM.

Condensate	Weight in grams			Total	Weight percent
	Na_2O	Al_2O_3	SiO_2		
Albite 500° C, 400 bars					
365	0.0039	0.0015	0.0231	0.0285	0.0078
447	0.0020	0.0027	0.0228	0.0275	0.0062
431	0.0040	0.0031	0.0171	0.0242	0.0056
894	0.0027	0.0039	0.0367	0.0433	0.0088
446	0.0012	0.0040	0.0213	0.0265	0.0054
Extra	0.0014	0.0026	0.0050	0.0090	
Total 2583	0.0152	0.0178	0.1260	0.1590	0.0062
Molecular ratios	1.00	0.71	8.63		
Albite 500° C, 1,000 bars					
518	0.0498	0.0108	0.2630	0.3236	0.0625
971	0.0887	0.1241	0.5038	0.7166	0.0738
1291	0.1800	0.1967	0.7007	1.0774	0.0835
835	0.0064	0.1073	0.4466	0.0603	0.0671
862	0.0795	0.1300	0.4960	0.7055	0.0818
Extra	0.0024	0.0341	0.0216	0.0581	
Total 4477	0.4068	0.6030	2.4317	3.4415	0.077
Molecular ratios	1.00	0.90	6.17		
Albite 500° C, 2,000 bars					
426	0.1189	0.1907	0.7722	1.0818	0.2539
252	0.0932	0.1070	0.4906	0.6908	0.2741
538	0.1694	0.3193	0.9913	1.4800	0.2751
Total 1216	0.3815	0.6170	2.2541	3.2526	0.2675
Molecular ratios	1.00	0.98	6.10		

The analysis of the condensed water was by conventional methods, as described in Hillebrand and Lundell.[6] SiO_2 was filtered off after evaporation to dryness with HCl, Al_2O_3 was separated by a double precipitation with ammonia, the ammonium salts in the filtrate removed with concentrated nitric acid by the J. Lawrence Smith method, and Na_2O weighed as Na_2SO_4.

[6] Hillebrand, W. H., and Lundell, G. E. F., Applied Inorganic Analysis, John Wiley and Sons, Inc., New York, 1929.

Table 4 gives detailed results of runs at 500° C, 400, 1,000, and 2,000 bars. At the lower pressure the albite is decomposed, as shown by the molecular ratios of the material dissolved in the steam, but at 2,000 bars it passes over in essentially the albite composition.

Microcline.

The microcline was from the Derry Mine, near Buckingham, Quebec, Canada, U. S. National Museum, No. 95998.[7] At 1,000 bars the same auxiliary bomb was used as described under albite, with results given for "Extra" in Table 5. In neither set of experiments did the orthoclase approach as near

TABLE 5.

SOLUBILITY OF MICROCLINE IN SUPERHEATED STEAM AT HIGH PRESSURE.

Condensate	Weight in grams			Total	Weight percent
	K_2O	Al_2O_3	SiO_2		
Microcline 500° C, 1,000 Bars					
950	0.1235	0.1199	0.4803	0.7237	0.0762
277	0.0236	0.0258	0.1110	0.1604	0.058
1011	0.1242	0.1326	0.5322	0.7890	0.058
559	0.0730	0.0748	0.2877	0.4355	0.078
873	0.1021	0.1121	0.4502	0.6644	0.076
Extra	0.0037	0.0035	0.0146	0.0218	
Total 3670	0.4501	0.4687	1.8760	2.7948	0.076
Molecular ratios	1.00	0.96	6.45		
Microcline 500° C, 2,000 Bars					
694	0.2523	0.2684	1.0733	1.5940	0.2297
876	0.3630	0.3863	1.5443	2.2936	0.2618
954	0.3787	0.3910	1.6629	2.4326	0.2550
940	0.3653	0.3261	1.5791	2.2704	0.2415
Total 3464	1.3593	1.3718	5.8596	8.5906	0.248
Molecular ratios	1.00	0.93	6.76		

to the 1 : 1 : 6 ratio as did albite at 2,000 bars; and at 2,000 bars the departure from the theoretical ratio is greater than at 1,000 bars. Whether or not this difference is significant cannot be told without further work at higher pressures and temperatures.

Enstatite.

The enstatite was from the Bishopville, S. C., Meteorite, U. S. National Museum, No. 971. It contained some sulfide, most of which was removed by treatment with dilute HCl. When steam first was passed over, H_2S was

[7] Most of the mineral specimens used in this work were given us by Dr. W. F. Foshag, Head Curator, Department of Geology, U. S. National Museum, to whom we express our gratitude.

evolved, but this soon ceased. All the runs were made at 1,000 bars, 600° C. The runs were made over a period of 10 days in the order in which they are given in Table 6. The SiO_2 content shows a distinct trend, dropping to less than one-half of the initial value, and coming to a fairly constant value of 0.056 percent. The solubility of quartz at this temperature and pressure is 0.559 percent. The values found for the MgO content are erratic, ranging from

TABLE 6.

THE SOLUBILITY OF ENSTATITE IN SUPERHEATED STEAM AT HIGH PRESSURE.

Weight condensate	Weight MgO	Weight SiO_2	Weight percent	
			MgO	SiO_2
600° C, 1,000 bars				
910	0.0815	1.2058	0.0090	0.1325
346	0.0488	9.4007	0.0141	0.1158
405	0.0519	0.3616	0.0128	0.0893
862	0.0696	0.6445	0.0081	0.0748
1059	0.1446	0.6628	0.0137	0.0626
1554	0.0707	0.8743	0.0046	0.0563
747	0.0637	0.4095	0.0083	0.0548
1028	0.0659	0.5614	0.0064	0.0546
608	0.0166	0.3334	0.0027	0.0548
1475	0.1774	0.8381	0.0120	0.0568
Total 8994	0.7907	6.2321	0.0088	0.069
Last five runs 5412	0.3943	3.0167	0.0073	0.056

0.0027 to 0.0141, with a mean of 0.009. It is evident that the enstatite is decomposed, with extraction of an amount of silica far in excess of the metasilicate ratio.

Sulfates.

Anhydrite, $CaSO_4$.—The solubility results at 500° C, 1,000 bars, are given in Table 7. The material used was from Hanover, Germany, U. S. National Museum, No. 94882. The average, obtained by dividing the total weight of $CaSO_4$ by the total weight of condensate, is only 0.002 percent, or twenty parts per million, and the large mean deviation is not surprising considering the smallness of the solubility.

Barite, $BaSO_4$.—The solubility results are given in Table 7. The barite used was from Cumberland, England, U. S. National Museum, No. R5926. The average is 0.004 percent, or 40 parts per million.

Anglesite, $PbSO_4$.—The sample used was from Tsumeb, S. W. Africa, U. S. National Museum, No. R8735. In these runs the auxiliary bomb was used as described under *Albite*. The average is 0.011 percent, or 110 parts per million.

Sodium Sulfate.—Runs were made at 67, 133, 666, and 1,000 bars with the results given in Table 7. No difficulty from stoppage of the pressure

tubing was encountered with Na_2SO_4, even at 1,000 bars, and there was no evidence of decomposition of the Na_2SO_4. The solubility of Na_2SO_4 in steam at 1,000 bars, 0.43 percent, or 4,300 parts per million, is the highest found at that pressure.

Hematite.

In all runs there was a small amount of iron oxide found in the condensate after evaporating to dryness. For example, the average of Fe_2O_3 found in the experiments with quartz at 500° C, 1,000 bars, was 0.002 percent. It was of interest to see if this corresponded to the saturation concentration, so a run was made with specular hematite at 500° C, 1,000 bars, with results shown in Table 8. The average of the first series of runs was 0.009 percent, indicating that in the quartz runs the steam was far from saturated with Fe_2O_3. In the next series of runs the bomb was filled with alternate layers of silica glass and hematite. The SiO_2 content of the steam fell off rapidly in the first three runs, until the gaseous solubility of quartz was reached, indicating that the glass

TABLE 7.

SOLUBILITY OF SOME SULFATES IN SUPERHEATED STEAM AT HIGH PRESSURE.

Weight condensate	Duration minutes	Rate grams per minute	Weight substance	Weight percent
		500° C, 1,000 bars		
		Anhydrite, $CaSO_4$		
543	510	1.06	0.0168	0.0031
1604	840	1.91	0.0248	0.0016
1336	840	1.59	0.0372	0.0028
832	440	1.89	0.0166	0.0020
Total 4315			0.0954	0.002
		Barite, $BaSO_4$		
970	475	2.04	0.0392	0.0040
937	960	0.98	0.0321	0.0034
1523	840	1.81	0.0587	0.0039
537	265	2.02	0.0156	0.0029
Total 3967			0.1456	0.004
		Anglesite, $PbSO_4$		
129	120	1.08	0.0172	0.0133
613	315	1.44	0.0773	0.0126
432	280	1.54	0.0293	0.0068
312	360	0.87	0.0240	0.0077
645	390	1.65	0.0529	0.0082
Extra			0.0317	
Total 2131			0.2324	0.011

TABLE 7—(*Continued*).

Weight condensate	Duration minutes	Rate grams per minute	Weight substance	Weight percent
		Sodium Sulfate		
		500° C, 67 bars		
598			0.0097	0.0016
524			0.0042	0.0008
1605			0.0095	0.0006
Total 2727			0.0234	0.0009
		500° C, 133 bars		
642			0.0269	0.0042
984			0.0334	0.0034
Total 1626			0.0603	0.0037
		500° C, 666 bars		
753	420	1.79	0.2073	0.0275
1405	860	1.63	0.3299	0.0235
Total 2158			0.5372	0.0249
		500° C, 1,000 bars		
404	195	2.07	1.7374	0.4301
665	315	2.11	2.8337	0.4261
1855	1260	1.63	8.0218	0.4324
Total 2924			12.5929	0.4307

had crystallized. The average SiO_2 content of the last three runs was 0.253, and the average found for quartz at 500° C, 1,000 bars, was 0.260. The first two runs also gave higher Fe_2O_3 content, and the average of the last three runs was 0.001, to be compared with an average of 0.009 for the runs with hematite alone. It appears that much of the Fe_2O_3 was held by the quartz. The higher Fe_2O_3 content of the first two runs, which also had a higher SiO_2 content, may be significant.

Cassiterite.

The cassiterite used was from Araca, Bolivia, U. S. National Museum, No. R2043. Several preliminary runs were made which showed the solubility was very small. A long run was then made at 500°, 2,000 bars. The duration of the run was 77 hours, the total weight of condensate 6255 g. From it was obtained a total residue on evaporation of 0.2113 g, of which 0.1823 g was Fe_2O_3, 0.0134 g was SiO_2, and 0.0156 g was SnO_2. This gives a solubility of 0.00025 percent, or 2.5 parts per million.

TABLE 8.

SOLUBILITY OF IRON OXIDE IN SUPERHEATED STEAM AT 500° C, 1,000 BARS.

Weight condensate	Weight SiO_2	Weight Fe_2O_3	Weight percent SiO_2	Weight percent Fe_2O_3
		Hematite		
851	—	0.0700	—	0.0082
157	—	0.0149	—	0.0095
252	—	0.0244	—	0.0097
Total 1260		0.1093		0.009
		Hematite and SiO_2 Glass		
2445	8.8119	0.0863	0.3600	0.0035
845	2.7997	0.0056	0.3313	0.0066
762	2.0327	0.0051	0.2668	0.0007
1042	2.6909	0.0068	0.2591	0.0007
2420	5.9426	0.0291	0.2456	0.0012
Total 7515	22.2868	0.1329	0.2965	0.001

Sulfides.

Several experiments were made with sulfides by a static method in which a weighed amount of the mineral was heated to 500° C at 1,000 bars. After the run, the change in weight was determined and the sample examined with the microscope. The minerals studied were bornite, covellite, bismuthenite, chalcocite, sphalerite, and pyrite. All except pyrite were essentially unaltered and did not show significant change in weight. For example, the bornite sample weighed 0.846 g; after the run it weighed 0.862 g, had some brownish spots and some very small recrystallized bornite on the surface. The pyrite sample weighed 1.138 g. After the run there was a strong smell of H_2S, the sample weighed 1.043 g and had a surface coating of pyrrhotite. A heavy rim of chalcocite had formed on the exposed edge of the copper washer.

The sphalerite sample was from Picos de Europa, Spain, U. S. National Museum, No. 106139. Two runs were made in the dynamic apparatus using the auxiliary bomb. Results are given in Table 9. The condensed liquid was black and had blackish flocculent aggregates floating in it. It immediately cleared up on acidifying with nitric acid, and the ZnO obtained was

TABLE 9.

THE SOLUBILITY OF SPHALERITE IN SUPERHEATED STEAM AT 500° C, 1,000 BARS.

Weight condensate	Weight ZnO
346	0.0482
717	0.0949
Extra	0.0377
Total 1063	0.1808
	Percent 0.17

brownish, probably from iron sulfide. There was a significant amount of material in the auxiliary bomb.

No more was done with sulfides because of pressure of other work. The small solubility of these sulfides is of interest. It would be worth while to carry out similar studies in slightly alkaline solutions, and further work by this method is needed.

SUMMARY.

An apparatus and method for determining the solubility of solids in superheated steam at high pressures have been described. Measurements were made at 400°, 500°, and 600° C and at pressures up to 2,000 bars. Materials studied include quartz, silica glass, albite, microcline, enstatite, anhydrite, barite, anglesite, sodium sulfate, hematite, and some sulfides.

ACKNOWLEDGMENT.

We wish to express our gratitude to Dr. W. F. Foshag, Head Curator, Department of Geology, U. S. National Museum, for his generous cooperation in furnishing the mineral specimens used.

THE GEOPHYSICAL LABORATORY,
CARNEGIE INSTITUTION OF WASHINGTON,
WASHINGTON, D. C.,
June 12, 1951.

CURRENT COAL RESEARCH—COAL RESOURCE STUDIES IN THE UNITED STATES DURING 1950.[1]

PAUL AVERITT.

THE industrial machine of the United States annually consumes prodigious quantities of energy. The mineral fuels and water power produced in 1949, for example, contained heat energy equivalent to 8 horsepower per person per day, which amount is twice the per capita production in 1900. The annual production of energy is still increasing at a rapid rate, as is well shown by the curve in Figure 1. Considering the potential future increase both in population and in use of energy, no one can say when the ascending curve will flatten.

With consumption of fuel resources on such an enormous and ever increasing scale, it is only prudent that we look ahead to the sources of fuel that will supply our future needs. When we take this look we discover a marked discrepancy between the production and reserves of petroleum and natural gas as compared with production and reserves of coal. As shown by Figure 2, petroleum and natural gas contributed 56 percent of the total energy consumed in 1949, whereas coal of all ranks contributed only 39 percent. Accepting the fact that the total ultimately available supply of petroleum and natural gas cannot be measured accurately, and ultimately may be found to constitute a much higher percentage of our total energy supply, the reserves of these fuels still appear to be relatively small as compared with reserves of coal, which unquestionably constitute a very large percentage of our total ultimately available supply of fuel. It follows, therefore, that sooner or later coal must be used in increasing quantities to aid in filling our fuel needs. Fortunately, coal can be adapted to meet practically all fuel requirements. We need only to work consistently now in order to be prepared for the day when the need for coal becomes general.

As we survey the coal investigations recently completed and now in progress, it is apparent that although much has been done toward filling the need for information about the distribution, quantity, and availability of our coal resources, the amount of work yet to be done is many times greater, and it is by no means assured that the necessary information can be developed as fast as it will be needed. The continuance of the modest program of coal investigation now in progress is therefore necessary if we are to be adequately prepared for the future.

Let us consider the status of information on coal reserves. For nine states —Pennsylvania, West Virginia, Illinois, Kansas, Montana, North Carolina,

[1] One of a group of papers given at a *Symposium on Current Coal Research in the United States*, joint session Society of Economic Geologists and A.I.M.E., St. Louis Meeting, February, 1951.

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Wyoming, New Mexico, and Michigan—summary reviews of the status of coal reserves information have been prepared during the past 20 years, and most of these summaries show that we have only fair knowledge of the coal resources.

For all of the remaining states there has not even been an adequate recent review of the status of available information. Even in the nine states where knowledge of coal resources is better developed than elsewhere, we are greatly

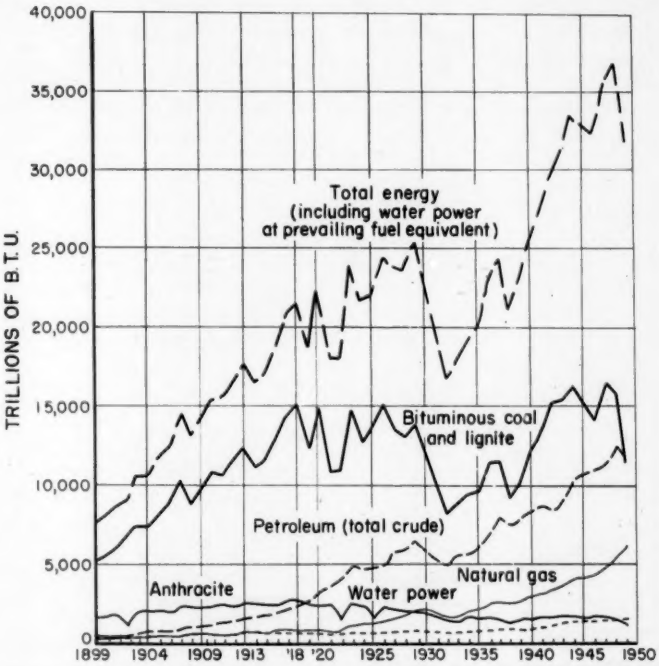


FIG. 1. Annual supply of energy from mineral fuels and water power in the United States, 1899–1949 (from U. S. Bur. Mines Mineral Market Report 1923, p. 13, October 20, 1950).

handicapped by the lack of information. To illustrate this point I call your attention to the status of information available on the coal resources of Wyoming, which has been the subject of a summary reserve study recently completed by the U. S. Geological Survey.[2] In summarizing all of the available information about the coal in Wyoming we found that the data were insufficient for the purpose of making reserve estimates in 53 percent of the coal-

[2] Berryhill, H. L., Jr., Brown, D. M., Brown, Andrew, and Taylor, D. A., Coal resources of Wyoming: U. S. Geol. Survey Circ. 81, Sept. 1950.

bearing area in the State. This was due to the fact that much of the coal-bearing area of Wyoming is concealed by younger rocks, and thus can be explored only by drilling. There are large areas of coal-bearing rock that have not been adequately explored in most of the coal-bearing states. Some of these areas are concealed by younger rocks, as in Wyoming; others are re-

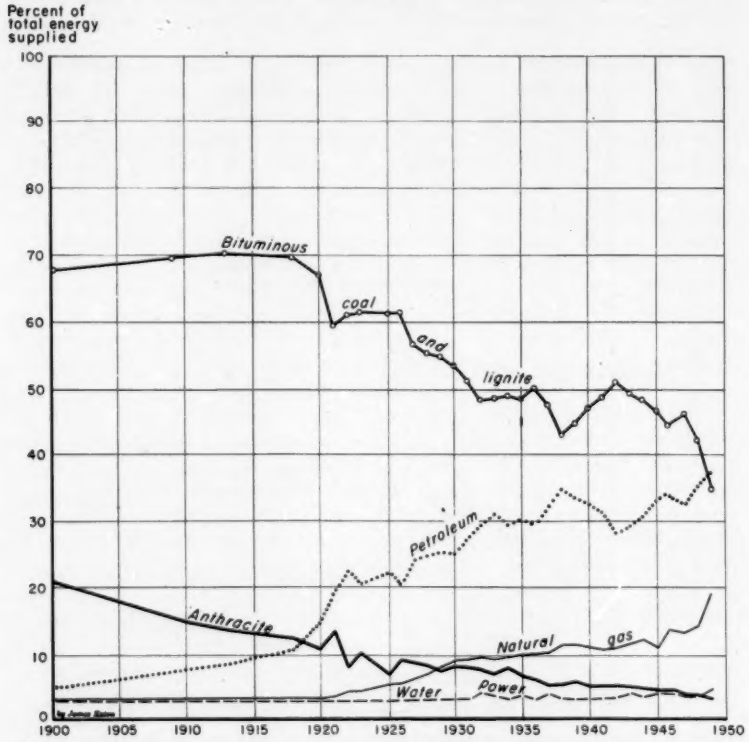


FIG. 2. Percentage of total energy supplied by mineral fuels and water power, 1900–1949 (data from U. S. Bur. Mines Mineral Yearbooks).

mote from transportation facilities or centers of use; others merely lie below local drainage and thus have not yet been deemed suitable for exploration.

In summarizing the available information in the remaining 47 percent of the coal-bearing area of Wyoming, we calculated reserves according to now fairly well standardized procedures, and made subdivisions into many categories according to the rank of the coal, thickness of overburden, relative amounts of reliable information available for making the estimates, and thickness of the individual beds. The results of this breakdown are shown on the

accompanying diagram. The diagram shows first the percentage distribution of reserves by rank. It will be noted that 10.9 percent of the reserves is bituminous coal, and 89.1 percent is subbituminous coal. The reserves within each rank are further divided according to thickness of overburden into three classes: 0 to 1,000, 1,000 to 2,000, and 2,000 to 3,000 feet. It is notable that 79.3 percent of the estimated reserves is in the 0- to 1,000-foot category and that successively smaller amounts are in the 1,000-to 2,000- and 2,000- to 3,000-foot categories. This is due simply to the fact that information is less abundant for the deeply buried beds. It is obvious that additional exploration at depth will make it possible to increase the estimates of reserves in the 1,000- to 2,000- and 2,000- to 3,000-foot categories. For much the same reason, only 3 percent of the reserves in Wyoming can be regarded as "measured," or proved; whereas 33 percent are "indicated," and 64 percent "inferred."

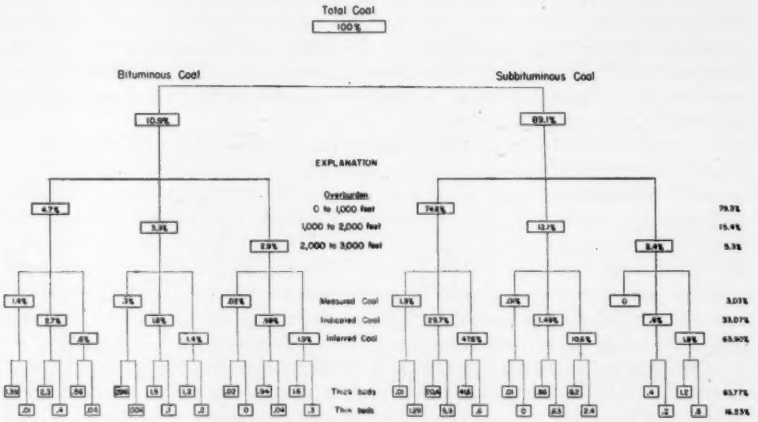


FIG. 3. Relative distribution by classes of recoverable coal reserves in Wyoming as appraised January 1, 1950.

Again, the larger percentages of "indicated" and "inferred" reserves are due to lack of precise data. Ideally, a much larger percentage of the reserves should be classifiable as "measured."

The relationships we have found in Wyoming are true to varying degrees for all the coal-bearing states. As nearly as I can estimate from the small quantity of data now available, only about 15 percent of the total estimated reserves of the United States can be regarded as "measured" reserves in beds 28 inches, or more, thick and under less than 2,000 feet of overburden. The remainder must be classed as "indicated" or "inferred" reserves, or is contained either in thin beds, or beds 2,000 to 3,000 feet below the surface, which are beyond the range of present economic interest. Obviously, a picture based on a high percentage of inferred data is subject to considerable change as new work is completed, and it is certain that the amounts of "measured" reserves

in the thicker and more accessible beds will be increased as exploration and development work is continued. The 15 percent figure is thus merely a convenient way of expressing the meagerness of our knowledge about coal reserves.

Most of the confusion and argument that exists about coal reserves stems in part from the lack of adequate quantitative information and in part from the fact that we are not all talking about the same thing when we use the words "coal reserves." To the marginal coal operator who has found it difficult to compete in the present market, the words "coal reserves" mean proved up, thick coal, with low ash and sulfur, a good roof rock, and lying under light overburden near transportation facilities and a center of consumption. At the other extreme, a few geologists tend to class all coal within certain broad limits as reserves, regardless of location, accessibility, or other purely economic factors. Both are right; one merely has an extremely short term view, the other a very long term view. Reserves of coal, or any other mineral resource, may be large or small, depending on the cutoff values assumed and on the viewpoint of the appraisor. It is therefore necessary that all statements of reserves be accompanied by an explanation of the methods and assumptions followed in preparing the estimate.

We have made a start at doing this in recent state appraisals prepared by the U. S. Geological Survey; and by adopting the procedure of reporting reserves in a number of specific categories according to rank, thickness of beds, thickness of overburden, and abundance of reliable information available for making the estimate, we are able for the first time to discuss the reserves of a few areas from a number of viewpoints. The general adoption of some such uniform policy of preparing and reporting coal reserves should ultimately remove a considerable part of the confusion attending discussions of reserves, and it will bring clearly into focus areas where additional work is needed.

I have prepared a longer paper on the coal resources of the United States,[3] in which I have set down all of the factual summary information about coal reserves that has come to my attention in the past few years. As copies of this paper are available to those who want them, I can be brief in my summary of work on coal resources in the United States during 1950. I must explain first that in preparing this summary I decided to restrict it to summary appraisals of reserves of counties or larger areas, and to omit detailed mapping projects, which are too numerous to mention in a short paper. However, I am sure we are agreed that detailed geologic mapping and exploration provide the major additions to our store of knowledge of coal reserves.

On this restricted basis, I am able to report that a considerable amount of summary work on coal reserves was completed and in progress in 1950. The U. S. Geological Survey published summary appraisals of the coal reserves in Michigan, Wyoming, and New Mexico during the year, and at the end of the year had work well advanced on similar appraisals for North Dakota, South Dakota, Indiana, and Virginia. The U. S. Bureau of Mines published reports on the minable reserves of coking coal in Cambria and Indiana counties,

[3] Coal resources of the United States, a progress report, November 1, 1950: U. S. Geol. Survey Circ. 94, December 1950.

Pa., and at the end of the year had similar work in progress in selected counties in Pennsylvania, West Virginia, and Kentucky. The Corps of Engineers, U. S. Army, had work in progress through contracts with engineering consultants on studies of possible sites for synthetic liquid fuel plants, which will include estimates of recoverable coal reserves in most of the coal-bearing states. The Illinois and Kansas Geological Surveys were engaged in summary appraisals of reserves in their respective states. Perhaps subsequent discussion will reveal additional summary work on reserves that I have not mentioned.

In conclusion, the work on coal resources in the United States during 1950 was on a scale comparable to that of 1949. Detailed geologic and coal-bed mapping projects by the U. S. Geological Survey and various state agencies were in progress in most of the coal-bearing states; summary reserve studies for a number of states and smaller areas were published. Although many years will pass before we have the desired full and complete knowledge of our coal resources, significant steps were accomplished during 1950, and it is to be hoped that the considerable volume of work in progress at the end of the year can be completed in 1951.

U. S. GEOLOGICAL SURVEY,
WASHINGTON, D. C.,
June 12, 1951.

CURRENT COAL RESEARCH—ACTIVITIES IN ARKANSAS.[1]

J. NORMAN PAYNE.

PRESENT coal research in Arkansas is in the stage of extreme infancy for it is only during the past two years that any substantial progress has been made. The work that had been done previously on the Arkansas coals has been chiefly along the line of stratigraphic studies, routine analyses, classification and mining methods. The more important contributions to information on the Arkansas coals were Winslow's report on the geology of the Arkansas coal regions in 1888 (1),[2] A. J. Collier's report on the Arkansas coal fields in 1906 (2), A. A. Steele's report on the coal-mining industry in 1910 (3), a compilation of available information on the geology of the Arkansas Valley by Carey Croneis in 1927 (4), analyses of Arkansas coals by A. C. Fieldner et al. published as a technical paper in 1928 by the U. S. Bureau of Mines (5), classification of the Arkansas coals by Hendricks in 1932 (6), and stratigraphic work by Hendricks and others (7, 8, 9).

Present research activities on coal in Arkansas fall into three categories: (1) geologic and stratigraphic studies involving the detailed mapping of the area not covered by Hendricks' report, (2) development and industrial research represented by stoker testing of Arkansas coals, and (3) fundamental research concerning the differential thermal behavior of different coal seams, and petrographic constituents of the Arkansas coals.

Research projects outlined for the future include detailed studies of the petrographic constitution of the Hartshorne, Charleston and Paris bed-coals, paleobotanical studies of the maceration residues of the above coals, and a study of the relationships between production of coal fines and structural position of the coal.

Geologic and Stratigraphic Studies.—At the present time the Institute of Science and Technology of the University of Arkansas has outlined a three year program designed to complete the detailed mapping of the area covered by the Arkansas coal fields. (The general coal field area as well as mapped and unmapped areas is shown in Figure 1.) During the summer of 1950 the mapping of the coal field area north of the Arkansas River in Franklin and Johnson counties was completed and a preliminary map and report is to be published during 1951. The mapping of the remainder of the coal field area is to be accomplished during the field seasons of 1951 and 1952 and a detailed report on the entire eastern portion of the coal field is to be published in 1953 or early 1954.

[1] One of a group of papers given at a *Symposium on Current Coal Research in the United States,* joint session of the Society of Economic Geologists and A.I.M.E., St. Louis Meeting, February, 1951.

[2] Numbers in parentheses refer to Bibliography at end of paper.

The coal field of Arkansas consists of more or less widely separated and isolated basins wherein the coal has been preserved from erosion in synclines. Two such basins were covered during the past summer's mapping program, namely, the Coal Hill-Spadra district and the Philpott basin.

Analysis of field and subsurface data in the Franklin and Johnson County area has not been completed so that no definite conclusions can be stated. However, some interesting facts have been developed. The formations exposed at the surface in Johnson County range in age from Pottsville to Alle-

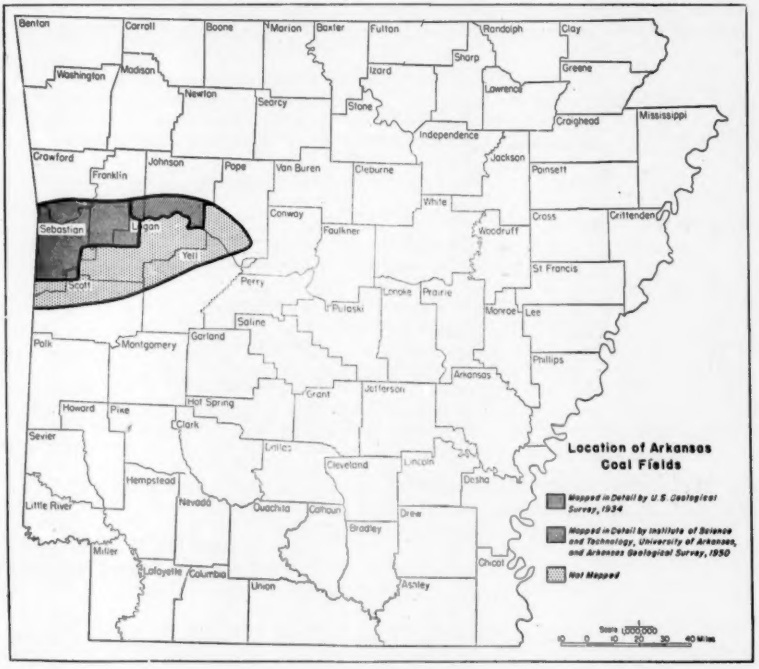
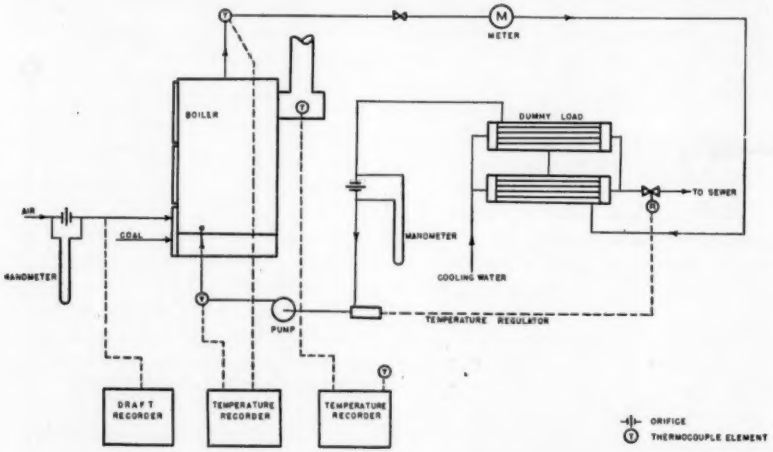


FIG. 1.

gheny, the lowest formation being the Atoka and the highest, Savanna. A feature of stratigraphic interest in this area is the rapid thinning of the sediments as the Ozark dome is approached. This thinning is best recorded in the decrease in interval between the Hartshorne and Charleston (Philpott) coals. The interval between the two coals in the Charleston basin in southern Franklin County is 800 feet, in southern Johnson County southeast of Clarksville it is approximately 600 feet, and in the Philpott Basin just south of the Ozark front it is 300 to 400 feet. The thinning in the case of the latter two points

is at the rate of 15 to 25 feet per mile. This decrease in thickness is probably a reflection of the distance from the source of sediments and of the presence to the north of the relatively positive element of the Ozark dome.

Another problem involved is in the thinning of the Hartshorne coal to the north. In the southern part of Johnson County the coal has an average thickness of 30 to 36 inches whereas in the Philpott basin it rarely exceeds 18 inches. A series of strip pits in southwestern Johnson County shed some rather interesting light on this problem. At the southern extremity of these pits the Hartshorne coal is about 30 inches thick with a persistent 1 to 2 inch middle band lying about 18 inches above the base of the coal. As the coal is followed northward it seems to thin persistently with all of the thinning taking



SCHEMATIC PLAN OF COMBUSTION TEST EQUIPMENT

FIG. 2.

place in the upper portion of the coal, until in the northern-most parts of the strip pits the upper coal and the middle-band have completely disappeared.

Details of stratigraphy and correlation of the Johnson County area must await final analysis of the field data, although it can be stated with some confidence that 4 to 6 more or less persistent coal beds or coal horizons do exist in the McAlester formation.

Stoker Fuel Studies.—The stoker testing studies of the Arkansas coals were undertaken primarily for economic reasons. Due to inherent characteristics of the coals in a number of districts in the Arkansas fields a disproportionate amount of slack or coal fines is produced, the amount running as high as 40 percent of the total tonnage produced. In ordinary times the market for this product is extremely limited and even though the western steel mills

and briquetting plants help the situation somewhat, the problem of disposing profitably of the screenings still exists. The stoker testing project was undertaken to try to alleviate this unfortunate condition.

The stoker testing equipment is patterned after the equipment set-up used by the Illinois Geological Survey (Fig. 2).

Laboratory analyses including proximate and ultimate analyses of the screened samples (each sample 4 to 4½ tons), sieve analyses, ash analyses of each sieve fraction, float-sink analyses, ash analyses of each float sink fraction are run.

Following laboratory analysis, screened and unscreened lots of each sample are burned on the following schedule:

1. Continuous burning for 12 hours.
2. Burning 45 minutes per hour for 12 hours total burning time.
3. Burning 30 minutes per hour for 12 hours total burning time.
4. Burning 15 minutes per hour for 12 hours total burning time.
5. Hold fire test for 48 hours burning 4 minutes per 1¼ hours.
6. Continuous burning for 2 hours.

During this schedule the fire is left undisturbed in so far as possible, and the air and water circulation rates are kept constant.

Tests are run to determine the following characteristics:

1. Uniformity of heat release. An overall average variation in the rate of heat release computed from the averages of each test condition.
2. Pickup—Expressed as the average and minimum heat release rates for the first 5 minutes of the operation 15 min. per 1 hour.
3. Response expressed as the average heat release rates in both the first 30 minutes and the first hour of continuous operation following the hold fire test.
4. Overrun of heating after load has decreased. Expressed similarly to pickup for the first 5 minutes after the stoker goes off during the test 15 min/hour. Maximum values are used.
5. Heat obtained. Expressed as heat delivered to the water per pound of coal.
6. Average efficiency. Expressed as the overall percentage of the heating value of the coal delivered to the water throughout the test.
7. Ease of fire maintenance.
8. Hold fire ability.
9. Objectionable features—odors, dust, etc.

Stoker burning tests have been run on samples of coal from the Hartford, Hackett-Excelsior, Paris, Philpott, and Spadra districts. These tests have shown that good stoker fuels can be prepared from the coals without washing, with the exception of the Spadra coal. The Spadra coal is semi-anthracite with a free swelling index of one, and it is necessary to blend strongly coking coals with it to obtain satisfactory results. On the other hand the coals from the other districts are rather strongly coking with free swelling indices of 6 to 8½ and would be more satisfactory in regard to coke tree formation if non-coking or weakly coking coals were blended with them. This makes for an ideal economic condition as the necessary blending materials are readily available.

Information is too sparse at the present time to permit of generalizations concerning the stoker behavior of Arkansas coals but with continued study it

is hoped to publish general and detailed results of this project within the next two years.

Differential Thermal Analysis.—Differential thermal curves have been run on three whole coal samples and one coke sample from Arkansas and one whole coal sample from Pennsylvania. The results show a direct relationship between the area under the exothermic curve, and the heating value of the coals expressed in BTU per pound as determined by the peroxide bomb method. This work has been carried on by Mr. Carl M. Gamel, Jr., and Dr. W. J. Smothers, of the Institute of Science and Technology, University of Arkansas.

This investigation is to be carried on in more detail. It is planned to run additional whole coal samples as well as differential thermal curves on the individual petrographic constituents, vitrain, clarain, etc. of each coal run.

UNIVERSITY OF ARKANSAS,
FAYETTEVILLE, ARKANSAS,
June 12, 1951.

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CURRENT COAL RESEARCH—COAL RESEARCH IN ILLINOIS.[1]

ARTHUR BEVAN.

RESEARCH on coal falls naturally into five categories of planning and procedure which have fundamental interrelations. According to the objectives of the investigation, the emphasis of the research projects will be upon 1) the geology of coal, 2) the petrography of coal, 3) the paleobotanical character and relations of coal, 4) the chemical character of coal and its relation to physical and chemical treatment, and 5) the engineering aspects of coal in a wide diversity of preparations and uses. Research in each of these phases is active in Illinois.

Coal Geology.—The geology of coal comprises research on coal as a rock, the coalification processes, stratigraphic and structural relations of coal beds, and relations of coal characteristics to the mining and preparation of coal. Comprehensive research in this field requires the use of all modern field and laboratory tools and techniques.

Research on the geology of coal in Illinois in recent years has been done chiefly by the staff of the Coal Division of the Geological Resources Section of the State Geological Survey, under the direction of Dr. G. H. Cady. Some stratigraphic studies have been made in the Department of Geology at the University of Illinois, in coöperation with the State Survey.

The State Geological Survey has long been engaged in intensive stratigraphic and structural studies of the coal beds and associated strata throughout the State, with the focus being upon the present and potentially important commercial deposits in the Illinois Basin in the southern part of the State. All types of data about these coals have been obtained from all available sources, with drill records and cores of outstanding value. As a part of the systematic investigation of the coal resources of the State, and to aid in the search for new acreages, tabulation is continually in progress of drill-hole data, including surface altitudes, depths of the coal, and thicknesses of commercial coal beds. Attention has been focused on the No. 6 (Herrin) coal of the southern and southwestern parts of the State and upon the coals in Vermilion County.

A large store of data has been interpreted, correlated, and mapped by counties. These maps show the altitudes of the coals, contoured surfaces of coal beds and other key members in the section, faults and cut-outs, mined-out areas, density of drilling in closely drilled areas—such as oil pools, and other useful geologic data. Much attention has necessarily been given to the

[1] One of a group of papers given at a *Symposium on Current Coal Research in the United States,* joint meeting of Society of Economic Geologists and A.I.M.E., St. Louis Meeting, February, 1951.

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preparation of logs and to the correlation of coal beds and key limestones. Detailed studies are in progress in areas in which coal beds are affected by faults and by sandstone cut-outs. The value of on-the-spot logging of diamond-drill cores has been strongly emphasized. During a recent 12-month period, a total of 21,106 feet of diamond-drill holes was logged by the geologists of the Coal Division. Investigation and interpretation are retarded by the lack of deep drill holes in certain critical areas. The value of the data would seem to justify drilling for the specific purpose of obtaining it. Recent drilling for oil has added much information on coal in the Illinois basin.

Several of the county projects have been completed and publications have been issued recently on some of them,[2] in addition to older published reports. Some reports have been completed in manuscript form, and others are in progress. The recent county maps and texts include Clay, Edwards, Effingham, Fayette, Gallatin, Jasper, Moultrie, Richland, Shelby, Wabash, Wayne, and White counties. The county studies of coal beds in the Illinois basin, except in Coles and Cumberland counties, have been completed.

A study of the stratigraphy and structural relations was recently made of the lower Pennsylvanian strata in the south-central part of the State and a report has been recently published.[3]

A major current project of the State Geological Survey is the systematic, up-to-date inventory of the coal resources of the State according to the formula of the plan adopted by the National Bituminous Coal Advisory Council. For this purpose, the area of coal-bearing rocks in Illinois has been subdivided into 33, complete and partial, rectangular areas, each of which includes one degree of longitude and one-half degree of latitude, or approximately 1,513 square miles. The data available in the files concerning the thickness of the coal beds determined from the records of coal mines, drill holes, and from outcrops have been plotted on base maps having a scale of 1 : 62,500. Thicknesses of coals more than 28 inches thick are delineated at approximately one-foot intervals by isopachs. Boundaries are drawn to distinguish areas of coal, over 28 inches thick, which are classifiable as proved, probable, strongly indicated, and weakly indicated. Planimetric surveys are then made of the mapped areas to obtain estimates on the coal tonnages in these four categories.

A study of the regional variations of the Pennsylvanian system throughout the United States is being made by Dr. H. R. Wanless of the Department of Geology of the University of Illinois. Especial attention is given to variations in thickness and lithology. More than 1,000 surface and subsurface columnar sections have thus far been compiled, including the Eastern Interior coal basin.

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Siever, Raymond, Structure of Herrin (No. 6) coal bed in Marion and Fayette counties and adjacent parts of Bond, Clinton, Montgomery, Clay, Effingham, Washington, Jefferson, and Wayne counties: Illinois Geol. Survey Circ. 164, 1950.

[3] Siever, Raymond, The Mississippian-Pennsylvanian unconformity in southern Illinois: Amer. Assoc. Pet. Geol. Bull., Vol. 35, No. 3, pp. 542–581, 1951; also, Illinois Geol. Survey Rept. Inv. 152, 1951.

Coal Petrography.—Petrographic research on coal is essentially a contribution to the understanding of the geology of coal, but it also has certain engineering applications. Both aspects of coal petrography are emphasized in the investigations of the Coal Division, Geological Resources Section, of the State Geological Survey. Emphasis has been placed upon the character and proportionate distribution of the banded ingredients—vitrain, clarain, durain, and fusain—of Illinois coals in the bed and in the prepared coal. In the engineering field, studies are in progress by the State Geological Survey on the effect of the mining and preparation processes on banded ingredient composition of the coal as marketed. Also comparative tests have been run in a domestic-type underfeed stoker to determine whether the conventional chemical tests provide a basis for judging the quality of coal for stoker use, to ascertain to what extent, if to any, the composition in terms of the banded ingredients—that is, the type of coal—affects combustion, and to learn the effects of preparation upon combustion behavior, including the effects of variations in size. To provide a basis for comparing the performance of Illinois coals, tests have also been run on out-of-state coals of a wide range of rank. The Coal Division is also coöperating with other agencies in the development of a standard code of stoker-boiler equipment and operation for testing the suitability of coals for such use. In connection with the determination of the type of coal used in the stoker tests, a technique of "broken" coal analysis was developed by B. C. Parks.[4]

Out of the coal-cleaning studies made in connection with the stoker combustion tests has come a report on "An Analysis of Coal Cleaning on a Concentrating Table." [5]

Other current research of the Coal Division includes thermal analysis, reflectivity, and X-ray investigation of coal as a possible means of reaching a more satisfactory and naturalistic basis of rank classification of coal than that now in use.

Some fundamental research with the electron microscope is being done by the Technological Institute at Northwestern University. Dr. Donald Dahlstrom, who is in charge of the project, reports that "the possibilities of the electron microscope are exceedingly bright in this much needed study."

It is well to emphasize that future petrographic research on coal should make all possible use of the tools and techniques of the electron microscope, trace elements studies, thermal analysis, and X-ray analysis, in addition to the more established procedures.

Coal Paleobotany.—Paleobotanical research is also necessary in order to gain a comprehensive insight into the geology of coal, as well as being helpful in stratigraphic correlation and important research of a botanical character. It is important to know the botanical constitution of the banded ingredients in coal, not only to decipher the natural history of the coal but in order to improve the petrographic classification of coal. In the State Geological Survey, special studies of the clarain, and particularly of variations in the bright and

[4] Parks, B. C., Petrographic analysis of coal by the particle count method: ECON. GEOL., vol. 44, pp. 376–424, 1949; also Illinois Geol. Survey Rept. Inv. 143, 1949.

[5] Boley, C. C., Illinois Geol. Survey Rept. Inv. 136, 1949.

dull clarain, are in progress. Precise studies of the spores associated with the coals are of great value in deciphering the original organic components of coal and in the correlation of coal beds. Some of the results of this recent Survey research have been published.[6] Continuous research along these lines is a part of the program of the Coal Division of the Geological Resources Section of the State Geological Survey.

A study was recently made of a boghead type of coal in Fulton County, so far as known a unique occurrence in Illinois, and a report is being published.[7]

A study of the phylogeny of Pennsylvanian seed ferns, based on stems, leaves, and fructifications, is being made by Prof. Wilson Stewart of the Department of Botany, University of Illinois. Miss Grace Somers, of the Geological Survey of Canada, is engaged in that Department on a special study of spores in the coals of Nova Scotia.

Geochemical Investigations.—The Geochemistry Section of the State Geological Survey, under the direction of Dr. Frank H. Reed, has several chemical and physical investigations of coal in progress, involving determinations of the fundamental chemical character of coal. One study pertains to the manner in which the constituent elements are linked together chemically, of direct concern in the use of coal as a chemical raw material.

To guide the selection of Illinois coals for the production of metallurgical coke, which has been becoming of increasing commercial importance in view of the depletion of eastern sources of coking coal, studies are under way of the oxidation of coal. This research bears upon coking properties and the storage of coal. Physico-chemical studies are being made on the ultra-fine structure of coal and coke, including measurement of pore space, in order to understand better the mechanism of coking, the changes produced by change in rank, and also the changes that take place in coal during its storage.

A report on the "Chemical Character of Banded Ingredients of Coal"[8] was published a few years ago.

A project under immediate consideration is an investigation of coals by spectroscopic and light absorption methods in order to obtain more precise data about the chemical character of coals.

Chemical Engineering Projects.—Several engineering projects dealing with coal are in progress in various places in Illinois.

It has been demonstrated by research work of the Geochemistry Section in the Applied Research Laboratory of the State Geological Survey that as much as 75 percent of certain coals in southern Illinois may be successfully blended with Pocahontas coal for the manufacture of metallurgical coke. These Illinois coals are now used for this purpose at an annual rate of one million tons.

Experiments are being made by Survey chemists and physicists upon the production of "char"—devolatilized coal—for possible use as a substitute for

[6] Kosanke, R. M., Pennsylvanian spores of Illinois and their use in correlation: Illinois Geol. Survey Bull. 74, 1950.

[7] Kosanke, R. M., A type of boghead coal from Illinois: Amer. Jour. Sci., vol. 249, pp. 444–450, June 1951.

[8] Rees, O. W., and others, Illinois Geol. Surv. Rept. Inv. 132, 1948.

low-volatile Pocahontas coal in the manufacture of metallurgical coke. Such coke with apparently satisfactory physical and chemical properties has been produced.

A fellowship project in the Department of Chemical Engineering at the University of Illinois deals with the kinetics of low-temperature carbonization in a fluidized bed. The University's Department of Mining and Metallurgical Engineering is investigating the mechanical properties of minerals and rocks. Phases of the investigation pertaining to coal involve research on 1) tensile and compressive strength and creep characteristics, 2) stresses around mine openings through the application of elastic laws to the behavior of coal and other rocks, and 3) problems of coal mine ventilation.

The Institute of Gas Technology, affiliated with the Illinois Institute of Technology in Chicago, is making a study of the gasification of coal for synthesis gas in the preparation of coal for combustion and carbonization, under the sponsorship of the American Gas Association. The projects comprise a study of the equilibria and kinetics in the reactions of carbon with oxygen and steam, and the gasification of pulverized coal in suspension in air, oxygen, and steam.

The Department of Chemical Engineering at Northwestern University, through the Technological Institute, is investigating coal washing by means of the cyclone type of centrifuge and the desliming of fine coal. Studies are also being made on the correlation of the final moisture contents of coals from mechanical dewatering devices, such as centrifugal machines and rotary filters.

The Singh Company of Chicago has undertaken a pilot plant development of the Singh process, under the sponsorship of the Illinois Coal Products Commission, for the production of char for 1) the manufacture of metallurgical coke, 2) smokeless briquets for stoker and hand-fired furnaces, 3) starting material for synthesis gas production, and 4) granular and pulverized industrial fuel. It is also investigating, as a part of this project, the production of tar at various devolatilization temperatures, aspects of fuel gas, and desulfurization of coal for the production of low-sulfur char and the recovery of elemental sulfur. Other projects in progress are the recovery of elemental sulfur from waste coal at mines and the production of coke briquets from char.

ILLINOIS STATE GEOLOGICAL SURVEY,
URBANA, ILL.,
June 12, 1951.

CURRENT COAL RESEARCH—COAL GEOLOGY IN KANSAS.[1]

WALTER H. SCHOEWE.

INTRODUCTION

As a coal state Kansas ranks 16th in the nation. Coal is superseded in value in Kansas only by petroleum, natural gas, and cement. At the present time the annual production in the State is around 2,000,000 tons valued at approximately $8,000,000. In its peak years Kansas produced annually 7,000,000 tons of coal. From 1869 when commercial coal production started to the end of 1949, a total of 261,371,483 tons of coal, valued at about $530,000,000, has been mined. This cumulative production is, however, only 19.15 percent of the State's known original minable coal of 1,409,590,000 tons. Currently more than 90 percent of all coal mined in Kansas is by the strip-mining method.

All the coal mined in Kansas today is Pennsylvanian in age. Formerly, a small amount of Permian coal was mined in Wabaunsee County and at least 300,000 tons of Cretaceous lignite was produced in the north-central part of the State. There are at least 53 coal seams in Kansas, of which 14 are being mined at present. In former years other Pennsylvanian coal beds were mined also. There are a number of thin coal seams in the Permian strata of Kansas, one of which has been mined commercially. The Cretaceous lignite of north-central Kansas occurs in the Dakota formation. Except for the lignite the Kansas coals are all of bituminous rank ranging from high volatile C to high volatile A coals.

Unlike the coals of many other mining states, the Kansas commercial coals are thin. The thickest mined coal seam in the State ranges from 32 to 42 inches in thickness. This seam, known as the Cherokee or Lower Weir-Pittsburg seam, is the one that has produced the most coal in Kansas. At present, however, the Mineral or Upper Weir-Pittsburg coal seam is most extensively mined. Its average thickness is about 22 inches. In Osage County the average thickness of the shaft-mined coal is 18 inches. Considerable 10-inch coal is strip-mined in the State.

The Kansas coal fields are in coal-producing district 15 as defined by the Bituminous Coal Act of 1937 and are part of the Western Region of the Interior Province. Coal is currently mined commercially in Kansas in eight counties, all of which are in the southeastern Kansas coal field. Formerly, coal was mined in 16 other eastern Kansas counties and in eight counties in the north-central part of the State.

[1] One of a group of papers given at a *Symposium on Current Coal Research in the United States*, joint meeting of the Society of Economic Geologists and A.I.M.E., St. Louis Meeting, February, 1951.

STATE GEOLOGICAL SURVEY OF KANSAS COAL INVENTORY STUDIES.

Origin of Coal Inventory Studies.—Although Kansas coals have been subject for study since 1898, first detailed inventories of coal resources in the State date to 1943. In the spring and summer of 1942 an examination of the coal-mining and petroleum industries in Kansas indicated to the Director of the State Geological Survey of Kansas that the people of Kansas might be found with a fuel shortage during the coming war winter. Such a fuel shortage seemed eminent because of the greatly increased demands not only for coal but also for oil and gas due to the rapidly expanding war industries located in the State, and to the lack of additional transportation facilities. It was, therefore, decided that the State Geological Survey undertake a complete inventory of its coal resources and gather all information possible on the coals of each one of the coal-bearing groups of rocks in the State. Since that time reports have been issued on the coals of the Douglas, Kansas City, and Waubaunsee groups of strata. The report on the Permian coal is now in press. Field work on the Cretaceous lignites of central Kansas has been completed and the report is now in the process of being written. This past summer field work was started on the coals of the Marmaton group of rocks in the eastern part of the State. A beginning on the main coal-bearing Cherokee formation has been made and three reports have thus far been published. In 1947 a 20-page report entitled "Coal Reserves in Kansas" was published by the State Geological Survey. This report, first compiled in December 1945 and distributed in mimeographed form, was subsequently revised in 1946 and printed in direct response to information requested by the Bituminous Coal Association.

In addition to the reports enumerated, other reports dealing with Kansas coal have been published. A comprehensive bibliography of these reports is given by Schoewe (1944, pp. 133–136) in Bulletin 52, part 3, of the State Geological Survey of Kansas.

Purpose and Nature of Studies.—The chief purpose of the coal investigations is to make a detailed study of the occurrence, distribution, and commercial reserves of Kansas coal deposits. The studies include the mapping and tracing of the coals throughout their geographical extent; locating all active and abandoned mines and plotting them on maps; determining the stratigraphic positions of the coals; studying the occurrence, physical nature, and thickness of the coals, character of the contact rocks, and the nature and thickness of the overburden. In addition, data concerning production, mines, mining methods, and history of mining are obtained from old settlers and miners living in the mining districts and from various State and Federal publications. Coal samples are collected and proximate analyses are made. The Survey has in its files copies of all published proximate analyses of Kansas coals. Finally, estimates of the coal reserves, both proved and potential, are calculated.

After the inventory studies have been completed it is planned to study the chemical nature and the technology of the Kansas coals. The coal studies will eventually be assembled in a comprehensive bulletin on Kansas coal.

COAL RESERVES.

The State Geological Survey of Kansas is coöperating with the Fuels Branch of the U. S. Geological Survey and the U. S. Bureau of Mines in their study of recalculating the coal resources of the United States. In Kansas the coal reserves are classified as proved (Measured and in part Indicated reserves of the U. S. Geological Survey) and potential (Inferred reserves of the U. S. Geological Survey) reserves. Proved coal reserves are those coals which can be mined with profit under existing conditions. All proved reserves are limited to active mining districts or places where definite thicknesses of the coal are known from outcrop, drill records, or actual mined coal seams. Potential coal reserve lands are the areas believed to be underlain by coal of given thicknesses. As used by the State Geological Survey of Kansas, the proved coal reserve refers to coal that lies within arbitrary limits of thickness and distance from a known occurrence. Those limits are based on past experience of the industry and geological observations in Kansas. The potential reserve is arrived at by regional stratigraphic projection.

In 1945 at the time the Kansas Survey made its original detailed inventory of the coal reserves of the State, no procedure for calculating proved coal reserves had been accepted generally by the various operating companies and scientific agencies. Also the suggested rules for calculating and reporting coal reserves issued by the Fuels Branch of the U. S. Geological Survey and distributed in 1949 were not available at the time the Kansas studies were made. As a result of the lack of definite methods of procedure, the State Geological Survey of Kansas adopted the following method for computing the State's bituminous coal reserves.

a. Minimum thickness of coal bed considered for strippable coal and all potential coal is 10 inches.

b. Reserve coal is considered to amount to 125 tons per acre-inch of coal. (The U. S. Geological Survey Fuels Branch is using 150 tons per acre-inch of coal in its computations and this is the figure used by the State Geological Survey in all of its revised computations.)

c. Preparation and mining losses were not considered; the calculated reserves are tons of coal in place.

d. Maximum depth of strip coal included in the calculations is 60 feet or the ratio of overburden to be stripped to the coal is not more than 35 cubic yards to 1 ton of coal.

e. Minimum thickness of reserve coal considered minable at various depths by underground methods is shown in the table below.

TABLE 1.

MAXIMUM DEPTH TO COAL PER MINIMUM THICKNESS OF COAL BEDS CONSIDERED MINABLE BY UNDERGROUND METHODS IN KANSAS.

Maximum depth to coal, feet	Minimum thickness of coal, inches
100	16
150	18
200	22
600	32
1,200	36

f. The method of computing an area of proved coal reserves is based on the following. A known thickness of coal at an outcrop, a drill hole, deep well, or in a mine is regarded as proving the presence of coal having the same thickness under 1 square mile. Two or more known occurrences of the same coal bed 4 miles or less apart and lying in the general direction of the strike are regarded as proving the coal to be continuous between these points. In the calculation of potential reserves a known thickness of coal at an outcrop, a drill hole, or in a mine is regarded as indicating the presence of coal of the same thickness under 400 square miles. The areas of both proved and potential coal calculated by these methods are in most cases greatly reduced from their maximum size by the location of drill holes or outcrops which indicate poor coal, thin coal, or no coal; by areas where the coal has been removed by erosion; or areas that extend across the state line.

Because of the variable nature of the Kansas lignite in regard to thickness, the scarcity of outcrops, and the general lack of information relative to the coal, it is extremely difficult to estimate the quantity of lignite unmined. On the basis of the standard used by the U. S. Geological Survey Fuels Branch in calculating lignite reserves, Kansas is essentially without lignite reserves. Except for local pockets, practically all the lignite mined in the State was 30 inches or less in thickness, the minimum thickness considered by the Fuels Branch as lignite reserve coal. As, however, more than 300,000 tons of lignite valued at approximately 1 million dollars was mined in Kansas and since lignite may again be mined in emergencies brought about by protracted coal strikes, railroad strikes, or fuel shortages of one kind or another or advances in coal technology, the Kansas lignites still underground are considered by the State Survey as emergency lignite coal reserves. In addition to the known thin seams of 30 inches or less in thickness, several areas in the State are reported to be underlain by lignite more than 30 inches thick. The lignites of such areas which are not associated with any mining activity but whose presence or occurrence is based on the veracity of the reports and suggested by broad geologic field relationships are here designated as alleged lignite reserves. In calculating the lignite reserves the standards used by the U. S. Geological Survey are followed.

The proved bituminous coal reserves in Kansas are calculated to be about 1,129,894,885 tons and the potential reserves 19,644,330,000 tons (on 150 tons per acre-foot basis). The emergency lignite reserves are estimated at 53,370,000 tons, whereas the alleged lignite reserves total 143,250,000 tons, making a grand total for all lignite coals in reserve 196,620,000 tons. The remaining reserves of all Kansas coals amount to 20,970,850,000 tons. Based on the average rate of production of coal in Kansas during the last 5 years (1946–1950) and assuming a 50 percent recovery of the unmined coal, the proved reserves should furnish employment for the coal miner for the next 225 years.

In addition to the coal inventory studies, Mr. Wallace B. Howe is making a detailed stratigraphic study of the Cherokee group involving the number and exact stratigraphic horizons of the coal seams in the group in southeastern Kansas. This study, sponsored by the State Geological Survey of Kansas, will be used by Mr. Howe as his Ph.D. thesis in the Department of Geology, University of Kansas.

NON-SURVEY PROJECTS.

In addition to the studies being made by the State Geological Survey of Kansas, Mr. William W. Hambleton, a graduate student in the Department of Geology, University of Kansas, is making a petrographic investigation of Kansas and Missouri coals. Thus far coal samples have been collected from three coal seams in four Kansas counties. The samples are thin-sectioned and polished coal columns are made. These are then studied microscopically under the petrographic microscope. In addition samples are analyzed chemically.

A study of coal balls associated with the coals of the Cherokee formation has been started by Dr. Robert W. Baxter, paleobotanist, of the Department of Botany, University of Kansas. Studies thus far indicate a very rich flora and a number of new species.

STATE GEOLOGICAL SURVEY,
UNIVERSITY OF KANSAS,
LAWRENCE, KANSAS,
June 12, 1951.

CURRENT COAL RESEARCH—COAL IN OKLAHOMA.[1]

ROBERT H. DOTT.

LITTLE work on coal is in progress in Oklahoma at the present time, and that little is incidental to stratigraphic work and areal mapping in connection with the preparation of a new Geologic Map of Oklahoma, especially in Craig and adjacent counties of northeastern Oklahoma, and in Sequoyah County, east-central Oklahoma.

About 10 years ago in a coöperative study by the U. S. Bureau of Mines, it was determined that low-volatile coal of the Hartshorne beds from LeFlore and eastern Haskell Counties, when blended with higher-volatile coal from the McAlester bed in Pittsburg County, and the Henryetta bed in Okmulgee County, makes a satisfactory metallurgical coke in by-product ovens. During and since World War II, Hartshorne and McAlester coals have been used at blast furnaces at Houston and Daingerfield, Texas, for making coke, and the low-volatile Hartshorne coal from eastern Oklahoma and western Arkansas has been shipped to Utah and California for blending with western coals to make blast-furnace coke.

Oklahoma Geological Survey Bulletins 67 and 68, on Haskell and Northern Le Flore Counties, respectively, published in 1948 and 1949, describe the occurrence and distribution of coal beds in these two areas.

OKLAHOMA GEOLOGICAL SURVEY,
NORMAN, OKLAHOMA,
June 11, 1951.

[1] One of a group of papers given at a *Symposium on Current Coal Research in the United States,* joint session Society of Economic Geologists and A.I.M.E., St. Louis Meeting, February, 1951.

THE SOLUBILITY OF GOLD.

KONRAD B. KRAUSKOPF.

ABSTRACT.

The solubilities of gold in various solutions as calculated from electrode potential and free energy data agree well with experimental results reported in the literature. In acid solutions gold dissolves as the ion $AuCl_4^-$. Formation of this ion requires that the solution contain excess Cl^-, and that it contain or be in contact with a fairly strong oxidizing agent. Naturally-occurring oxidizing agents whose effectiveness has been demonstrated both experimentally and theoretically are MnO_2, O_2, Fe^{+++} and Cu^{++}. Neither H^+ nor SO_4^{--} is sufficiently strong as an oxidizing agent to affect gold appreciably at ordinary temperatures. In naturally-occurring alkaline solutions gold is not significantly soluble unless sulfide is present. In sulfide solutions gold is carried as a complex ion, probably AuS^-; the fact that gold metal is soluble in HS^- solutions at ordinary temperatures indicates that this ion is an exceptionally stable one. The effect of temperature on the solubility of gold cannot be predicted from available thermodynamic data, but experiments indicate that the solubility increases with rising temperature in both acid and alkaline solutions.

INTRODUCTION.

DESPITE its chemical inertness, gold is sufficiently soluble to explain the known facts about its transportation in vein fluids and surface waters. Experimental work on the solubility of gold is voluminous, and the more recent papers provide fairly consistent data. The data have been ably summarized by Ogryzlo (1),[1] Smith (2) and Zvyagintsev and Paulsen (3). The purpose of the present paper is to show that the experimental results and geologic observations check reasonably well with predictions from thermodynamic data on gold solutions.

THERMODYNAMIC DATA.

The pertinent data are the standard electrode potentials in Table I and the standard free energies of formation in Table II, both taken from Latimer (4). Either the electrode potentials or the free energies permit calculation of how far any given reaction will proceed. The electrode potentials provide the most direct means of calculation for oxidation-reduction processes; the free energies, although more cumbersome, are applicable to any reaction, whether it involves oxidation-reduction or not.

The data of Tables I and II apply to solutions at a temperature of 25° C. and having concentrations of 1 mole/liter with respect to all soluble substances. Calculations for different concentrations are easy, but calculations for higher or lower temperatures cannot be made without further data.

[1] Numbers in parentheses refer to Bibliography at end of paper.

TABLE I

STANDARD ELECTRODE POTENTIALS AT 25° C (IN VOLTS) (FROM LATIMER, 4)

In acid solutions:		
(1)	$H_2 = 2H^+ + 2e^-$	0.000
(2)	$H_2SO_3 + H_2O = SO_4^{--} + 4H^+ + 2e^-$	− 0.20
(3)	$CuCl_2^- = Cu^{++} + 2Cl^- + e^-$	− 0.5
(4)	$Fe^{++} = Fe^{+++} + e^-$	− 0.771
(5)	$Au + 4Cl^- = AuCl_4^- + 3e^-$	− 1.00
(6)	$2H_2O = O_2 + 4H^+ + 4e^-$	− 1.229
(7)	$Mn^{++} + 2H_2O = MnO_2 + 4H^+ + 2e^-$	− 1.28
(8)	$Cl^- = \frac{1}{2}Cl_2 + e^-$	− 1.358
(9)	$Au = Au^{+++} + 3e^-$	− 1.42
(10)	$Au = Au^+ + e^-$	− 1.68
In basic solutions:		
(11)	$OH^- + Fe(OH)_2 = Fe(OH)_3 + e^-$	+ 0.56
(12)	$OH^- + Mn(OH)_2 = Mn(OH)_3 + e^-$	+ 0.40
(13)	$H_2O + 2OH^- + Cu_2O = 2Cu(OH)_2 + 2e^-$	+ 0.09
(14)	$4OH^- = O_2 + 2H_2O + 4e^-$	− 0.401
(15)	$Au + 4OH^- = AuO_2^- + 2H_2O + 3e^-$ ca.	− 0.5

The biggest gap in presently available physico-chemical data for gold, as for most other substances of interest in economic geology, is the lack of information at high temperatures. In the present paper we can only make calculations for 25° and then indicate probable directions of variation as the temperature changes.

Before undertaking numerical calculations, we can make a few qualitative predictions at once from Table I. The table is arranged in the usual manner, with the reduced form of each electrode reaction on the left and the oxidized form on the right, and with the oxidized form increasing in oxidizing power downward. This means that the oxidized form of any couple will react readily with the reduced form of any couple above it in the series, but will not react (or will react only to a slight extent) with the reduced form of a couple below it. It is immediately apparent, then, that gold cannot be soluble in ordinary acids, because all of the gold ions ($AuCl_4^-$,

TABLE II

STANDARD FREE ENERGIES OF FORMATION AT 25° C
(IN CALORIES/MOLE) (FROM LATIMER, 4)

Cl^-	− 31,330	H^+	0
$CuCl_2^-$	− 58,300	$H_2O(l)$	− 56,690
Cu^{++}	+ 15,910	OH^-	− 37,585
$AuCl_4^-$	− 56,200	$H_2S(aq)$	− 6,520
Fe^{++}	− 20,310	HS^-	+ 2,950
Fe^{+++}	− 2,530	S^{--}	+ 23,420
Mn^{++}	− 48,600	SO_4^{--}	− 176,100
MnO_2	− 102,900	$H_2SO_3(aq)$	− 128,535

Au^{+++} and Au^{+}) are well below the H_2—H^+ couple. In other words, the gold ions should be reduced by molecular hydrogen to gold metal, but the metal would not be dissolved by hydrogen ion. Also the table shows at once that neither of the simple gold ions, Au^+ or Au^{+++}, can exist in solution in geologic environments, since these ions are stronger oxidizing agents than free chlorine. On the other hand, reactions 5 and 7 suggest that gold may be oxidized by MnO_2 in acid solution, provided that Cl^- is present to form $AuCl_4^-$. Free oxygen should also be capable of oxidizing gold in acid solution (reactions 5 and 6). Solutions of ferric ion, Fe^{+++}, and cupric ion, Cu^{++}, are weaker oxidizing agents than $AuCl_4^-$; nevertheless the potentials of reactions 3 and 4 are close enough to the potential of reaction 5 so that with high concentrations these ions might be capable of bringing minute amounts of gold into solution. These predictions and others will now be examined quantitatively.

METHOD OF CALCULATION.

To say that gold is not soluble in acid means more precisely that the solubility in acid is extremely small. Just how small it is can be calculated from an equation obtained by combining electrode reactions 1 and 5:

$$Au + 3H^+ + 4Cl^- = AuCl_4^- + 3/2H_2 \qquad (16)$$

Subtraction of the electrode potentials gives for the electromotive force of this reaction

$$E = -1.00 - 0.00 = -1.00 \text{ volts}$$

From this figure the free energy change for the reaction is derived by the relation

$$\Delta F^\circ = -nfE$$

where ΔF° means the free energy change at 25° C when the concentrations of H^+, Cl^- and $AuCl_4^-$ are 1 mole/liter (1M) and the pressure of H_2 is 1 atmosphere; n is the number of electrons transferred, as shown by the equation (in this case $n = 3$, since each Au atom loses 3 electrons and each of 3 hydrogen ions picks up 1 electron); and f is the Faraday constant, 23,066 cal/volt/equivalent. Substituting,

$$\Delta F^\circ = -3 \times 23{,}066 \times (-1.00) = +69{,}200 \text{ cal}$$

This same result can also be obtained by adding free energies of formation from Table II for all the substances in equation 16. By definition, the free energy of formation of an element (in its standard state) is zero, and the free energy of formation of H^+ in 1M solution is also defined as zero. From Table II, the free energy of $AuCl_4^-$ is −56,200 cal, and that of Cl^- is −31,330. Hence

$$\begin{aligned}\Delta F^\circ &= \text{free energy of products} - \text{free energy of reactants} \\ &= -56{,}200 + 3/2 \times 0 - 0 - 3 \times 0 - 4 \times (-31{,}330) \\ &= -56{,}200 + 125{,}320 = +69{,}120 \text{ cal}\end{aligned}$$

The slight discrepancy between 69,200 calculated from electrode potentials and 69,120 calculated directly from free energies is of no consequence for present purposes. So many variables are uncontrolled in the geologic environments to which these calculations will be applied that we can hope for no more than order-of-magnitude figures.

A high negative electromotive force like the -1.00 volt of the present example, and a high positive ΔF like the 69,200 cal of this example, both indicate that the reaction is displaced far to the left at equilibrium—in other words, that the amount of gold which will go into $AuCl_4^-$ is inappreciable. To get a figure for the amount, we need a value for the equilibrium constant of equation 16, which can be calculated from the relation

$$\Delta F^\circ = -RT \ln K$$

in which R is the gas-law constant, 1.987 cal/mole; T is absolute temperature; and K is the equilibrium constant. For present purposes T will be uniformly 298°, so that the formula can be rearranged and simplified as follows:

$$\begin{aligned} \log K &= \ln K/2.303 \\ &= -\Delta F^\circ/2.303RT \\ &= -\Delta F^\circ/2.303 \times 1.987 \times 298 \\ &= -\Delta F^\circ/1365 \end{aligned}$$

The factor 2.303 is introduced to change natural logarithms to decimal logarithms. In the present example,

$$\log K = -69{,}200/1365 = \text{ca.} -51$$

$$K = \frac{(AuCl_4^-)(H_2)^{3/2}}{(H^+)^3(Cl^-)^4} = 10^{-51}$$

Strictly $\log K$ turns out to be -50.7, but the approximate value, -51, is more than sufficiently accurate for this calculation. If now we suppose that the acid concentration is 1M ($H^+ = 1$, $Cl^- = 1$), and if we suppose further than no H_2 is present except what is produced in the reaction (making the number of moles of H_2 always 3/2 the number of $AuCl_4^-$), we may substitute in the equation for K:

$$K = \frac{(AuCl_4^-)(3/2 \times AuCl_4^-)^{3/2}}{(1)^3(1)^4} = 10^{-51}$$

$(AuCl_4^-)^{5/2} = 0.55 \times 10^{-51}$; approximately $AuCl_4^- = 10^{-20}$ mole/liter. Hence the amount of Au in solution is 10^{-20} gram-atom or approximately 2×10^{-18} gram/liter (atomic weight of Au = 197, approximately 2×10^2). In other words, the solubility of gold in 1M HCl is so small that the concentration of dissolved gold would be equivalent to about 1 gram in a volume of water equal to that in the Gulf of Mexico. Raising the concentration of acid to 10M would increase the solubility 1,000 times, but the

amount of gold in solution would still be negligibly small (2×10^{-15} gram/liter).

For a second example, consider the effect on gold of MnO_2 in contact with an acid chloride solution. The equation is a combination of electrode reactions 5 and 7:

$$2Au + 12H^+ + 3MnO_2 + 8Cl^- = 3Mn^{++} + 2AuCl_4^- + 6H_2O \quad (17)$$

Using the same procedure as before, we obtain $E = +0.28$ volt, $\Delta F^\circ = -38{,}000$ cal, and $K =$ ca. 10^{28}. The positive electromotive force, negative free energy change, and large equilibrium constant all mean that equation 17 is displaced far to the right; in other words, that gold is readily soluble in a mixture of MnO_2 and 1M HCl. The large coefficients of H^+ and Cl^- in equation 17, however, mean that the solubility is very sensitive to changes in the concentrations of these ions. In order to calculate the effect of concentration, we set up the expression for the equilibrium constant,

$$K = (Mn^{++})^3(AuCl_4^-)^2/(H^+)^{12}(Cl^-)^8 = \text{ca. } 10^{28}$$

We assume that no Mn^{++} is present except what is produced in the reaction; in other words, 3/2 moles of Mn^{++} will be present for every mole of $AuCl_4^-$. (If more Mn^{++} is present, the solubility will be decreased.) Then

$$(AuCl_4^-)^5 = 8/27 \times 10^{28} \times (H^+)^{12}(Cl^-)^8$$

From this equation the concentrations in Table III are calculated. The figures are only approximate, since we are concerned here only with orders of magnitude.

TABLE III.

SOLUBILITIES OF GOLD IN HCl + MnO_2 AT 25° C.

Concentration of		Solubility of Au	
H^+ (mole/l)	Cl^- (mole/l)	mole/l	gram/l
10^{-4}	1	10^{-4}	0.02
10^{-6}	1	$10^{-6.5}$	10^{-4}
10^{-6}	1	10^{-9}	2×10^{-7}
1	10^{-4}	0.1	20
1	10^{-6}	10^{-4}	0.02
1	10^{-8}	10^{-7}	2×10^{-5}
10^{-2}	10^{-2}	10^{-3}	2
10^{-3}	10^{-3}	10^{-6}	2×10^{-4}
10^{-4}	10^{-4}	10^{-10}	2×10^{-8}

If we select 10^{-6} gram/liter (1 part per billion) as an arbitrary dividing line between significant and non-significant concentrations of gold, Table III indicates that the metal is appreciably soluble in the presence of MnO_2 in HCl more dilute than 0.001M, or in still smaller concentrations of either H^+ or Cl^- provided the other is present in large amount. Concentrations of H^+ of 0.001M and higher are not uncommon in geologic environments, especially in the oxidized zones of ore deposits; so high a concentration of Cl^- is less common, but concentrations up to 0.025M are reported in a few

mine waters (see analyses in Emmons (5), pp. 87–89, and Clarke (6), pp. 646–647).

It should be noted that the driving force of the MnO_2 reaction is not, as is commonly stated, the formation of Cl_2 or of "nascent" chlorine. As Table III shows, gold is dissolved in appreciable amounts by concentrations of HCl far too small to produce chlorine by reaction with MnO_2. The reaction goes because of the great stability of $AuCl_4^-$; the function of the MnO_2 is to oxidize the gold, and the function of the Cl^- is to tie up the oxidized gold in this ion. The solution must be acid because MnO_2 is an effective oxidizing agent only in the presence of H^+.

The method of calculation illustrated by these two examples will be used for other reactions in the following sections.

SOLUBILITY OF GOLD IN ACID SOLUTIONS.

For gold to dissolve in an acid solution requires two things: the presence of chloride ion (to form $AuCl_4^-$) and the presence of an oxidizing agent considerably stronger than H^+ alone. These requirements eliminate HCl and other common acids, by themselves, as solvents for gold. The inability of acids to affect the metal (except at high temperatures) has been demonstrated experimentally for inorganic acids by Ogryzlo (1) and others, and for organic acids by Fetzer (7).

The reaction with MnO_2 and HCl discussed in the last section is the one which Emmons long ago (8, pp. 405–408) suggested for the transportation of gold in supergene waters, and which he demonstrated both by experiment and by field observation.

Besides MnO_2, a few other naturally-occurring oxidizing agents are capable of oxidizing gold in acid chloride solutions. One is atmospheric oxygen, for which a reaction may be written by combining electrode reactions 5 and 6:

$$2Au + 6H^+ + 3/2O_2 + 8Cl^- = 2AuCl_4^- + 3H_2O \qquad (18)$$

Calculation gives $E = +0.23$ volt, $\Delta F^\circ = -32{,}000$ cal, $K =$ ca. 10^{23}. Like the MnO_2 reaction, this one is sensitive to changes in H^+ and Cl^-. Table IV shows the solubility of gold at representative values of these ions. on the assumption that O_2 has a constant partial pressure of 0.2 atmosphere,

TABLE IV.

SOLUBILITY OF GOLD IN HCl + O_2 AT 25° C.

Concentration of		Solubility of Au	
H^+ (mole/l)	Cl^- (mole/l)	mole/l	gram/l
1	1	high	high
10^{-4}	1	0.1	20
10^{-6}	1	10^{-7}	0.00002
10^{-7}	1	10^{-10}	2×10^{-8}
1	10^{-4}	10^{-5}	0.002
1	10^{-6}	10^{-9}	2×10^{-7}
10^{-2}	10^{-2}	10^{-3}	0.2
10^{-3}	10^{-3}	10^{-10}	2×10^{-8}
10^{-2}	10^{-3}	10^{-7}	2×10^{-5}

The table indicates that gold should dissolve appreciably in well-aerated surface waters of only slight acidity, provided that the concentration of Cl^- is high. If Cl^- is low (say, below 0.001M or 35 p.p.m.), the acidity required is above that to be expected in natural waters. Under any circumstances the reaction will be very slow, as are most processes involving molecular oxygen.

Another possible oxidizing agent is ferric ion, Fe^{+++}:

$$Au + 3Fe^{+++} + 4Cl^- = AuCl_4^- + 3Fe^{++} \qquad (19)$$

for which $E = -0.23$ volt, $\Delta F^\circ = +16{,}000$ cal, K = ca. 10^{-12}. Ferric ion, of course, is a much weaker oxidizing agent than either O_2 or MnO_2, a fact which is reflected in the positive free energy change and the small K. Nevertheless, with sufficiently high concentrations of Fe^{+++} and Cl^-, gold is appreciably soluble, as Table V shows. The theoretical figures in Table V check fairly well with experiments described in the literature. McCaughey (9) reports that gold dissolved slowly at 38–43° C in a solution containing

TABLE V.

SOLUBILITY OF GOLD IN $Fe^{+++} + Cl^-$ AT 25° C.

Concentration of		Solubility of Au	
Fe^{+++} (mole/1)	Cl^- (mole/1)	mole/1	gram/1
1	1	5×10^{-4}	0.1
0.1	0.1	10^{-5}	0.002
0.01	0.01	10^{-7}	2×10^{-5}
0.001	0.001	5×10^{-9}	10^{-6}
1	10^{-5}	5×10^{-9}	10^{-6}
10^{-6}	1	10^{-8}	2×10^{-6}

about 0.1M Fe^{+++} and about 2.4M Cl^-, reaching 0.023 gram/liter after 185 hours, but equilibrium had not yet been attained. With these concentrations the theoretical solubility at 25° is about 0.035 gram/liter, which agrees with the experimental figure as closely as can be expected. Brokaw (10), working with solutions of 0.1M Cl^- and 0.03M Fe^{+++}, reports no detectable solution of gold at 18–25° C. The theoretical solubility under these conditions would be about 0.0006 gram/liter, or about 0.00003 gram in the 50 cc samples which Brokaw used. Since Brokaw was using a balance sensitive to 0.00001 gram, he should have been barely able to detect a solubility of this magnitude. The fact that he did not may mean that equilibrium had not been reached even after the 34 days of his experiment, or that his $FeCl_3$ contained a trace of $FeCl_2$, or that the thermodynamic data are somewhat inaccurate. In any event it seems clear that $FeCl_3$ must be fairly concentrated to affect gold significantly.

The effect of Fe^{++} in decreasing the solubility of gold, which would be predicted from equation 19, is borne out by McCaughey's observation that less gold was dissolved in solutions to which $FeSO_4$ had been added. Statements in the older literature that gold can be dissolved by ferric sulfate or by ferric sulfate plus sulfuric acid have been repeatedly proved wrong by experiment (1), and are likewise refuted by the above thermodynamic

data. Compounds of ferric ion can affect gold only when Cl^- is present to form $AuCl_4^-$.

Another conceivable oxidizing agent is cupric ion, Cu^{++}:

$$Au + 3Cu^{++} + 10Cl^- = AuCl_4^- + 3CuCl_2^- \quad (20)$$

for which $E = -0.50$ volt, $\Delta F^\circ = 34{,}500$ cal, $K =$ ca. 10^{-25}. From these data a solubility of about 0.0001 gram/liter may be calculated for concentrations of Cu^{++} and Cl^- both 1M at 25° C. McCaughey (9) reports a minimum solubility of 0.0018 gram/liter for concentrations of 2.4M Cl^- and 0.13M Cu^{++} at 38–45° C, conditions for which the theoretical figure would be 0.0002 gram/liter at 25° C. The agreement between theory and experiment is poor, but both indicate clearly that Cu^{++} has less effect on gold than Fe^{+++}, and that gold can dissolve in copper solutions under natural conditions only if concentrations of both Cu^{++} and Cl^- are abnormally high.

An oxidizing agent weaker than Cu^{++} cannot affect gold appreciably at ordinary temperatures. This may be illustrated by considering another possible naturally-occurring oxidizing agent, sulfuric acid. This substance can act as an oxidizing agent in two ways: (1) by the addition of an electron to H^+, forming H_2; (2) by the addition of two or more electrons to the sulfur of SO_4^{--}, forming H_2SO_3, S, or H_2S. The inadequacy of H^+ as an oxidizing agent for gold has been demonstrated above; the inadequacy of SO_4^{--} may be shown by combining reactions 2 and 5 from Table I:

$$2Au + 8Cl^- + 12H^+ + 3SO_4^{--} = 2AuCl_4^- + 3H_2SO_3 + 3H_2O \quad (21)$$

In this equation SO_4^{--} is given the benefit of everything that will help it act as an oxidizing agent—an acid solution, and an adequate supply of Cl^- to unite with the oxidized gold. Calculation gives $E = -0.8$ volt, ΔF° = ca. + 110,000 cal, and $K = 10^{-81}$. If Cl^-, H^+ and SO_4^{--} all have concentrations of 1M, and if no H_2SO_3 is present except that produced in the reaction, the solubility of gold is about 10^{-16} mole/liter or 2×10^{-14} gram/liter. Hence even at concentrations greater than could be expected in natural solutions the solubility is negligibly small.

In summary, oxidation-reduction potentials indicate that gold should be soluble at normal temperatures in acid waters containing Cl^- and any one of several moderately strong oxidizing agents (MnO_2, O_2, Fe^{+++}, Cu^{++}). The solubilities indicated, however, are appreciable only under conditions which would be fairly uncommon in nature. This conclusion agrees with experimental results and with the observation that gold is sometimes transported in supergene waters, but only locally and in small amounts.

SOLUBILITY OF GOLD IN ALKALINE SOLUTIONS.

In alkaline solution $AuCl_4^-$ becomes unstable, changing to AuO_2^- if sulfide is not present:

$$AuCl_4^- + 4OH^- = AuO_2^- + 2H_2O + 4Cl^-$$

The free energy change for this reaction, calculated from the figures in Table II, is − 34,000 cal, the high negative value indicating the much greater stability of AuO_2^-. In any solution not containing sulfide ion and having a pH over 8, AuO_2^- should be the dominant ion.

Gold should be dissolved by strongly basic solutions, with atmospheric oxygen acting as the oxidizing agent, according to the reaction (from electrode reactions 14 and 15, Table I):

$$2Au + 3/2O_2 + 2OH^- = 2AuO_2^- + H_2O \qquad (22)$$

For this reaction E = ca. − 0.1 volt, $\Delta F°$ = ca. + 14,000 cal/mole, and K = ca. 10^{-10}. In 1M OH^-, if the partial pressure of O_2 is 0.2 atmosphere, the solubility of gold should be about 0.001 gram/liter; in 0.0001M OH^- (about the upper limit of alkalinity in naturally-occurring solutions) the solubility is only 10^{-6} gram/liter. In nature at ordinary temperatures, therefore, gold should not be appreciably affected by atmospheric oxygen in the presence of alkaline solutions. Nor can any form of iron, copper or manganese affect the metal in alkaline solution, since $Fe(OH)_3$, $Cu(OH)_2$ and $Mn(OH)_3$ are relatively feeble oxidizing agents; comparison of electrode potentials for reactions 11, 12, 13 and 15 in Table I shows this relationship clearly.

For alkaline solutions containing sulfide ion, chemical data are scanty and the problem is more complicated. The artificially prepared gold sulfide, AuS, is known to be soluble in excess S^{--} and S_x^{--} (Mellor (11), pp. 610–614), proving the existence of some kind of complex sulfide ion. Smith (2) and Latimer and Hildebrand (12) consider AuS^- as the most probable ion, although some AuS_2^- may form also. Experimentally, one of the most perplexing facts about the chemistry of gold is its ability to dissolve in solutions of HS^- of moderate concentration even at room temperature, whereas it dissolves in S^{--} (i.e., more alkaline solutions) only in concentrated solutions at high temperature. This characteristic of gold has been demonstrated by Ogryzlo (1), by Zvyagintsev and Paulsen (3), and by Lindner and Gruner (13). None of these authors have suggested a mechanism for the reaction.

The difficulty is that in order to dissolve gold it must be oxidized, and a solution of NaHS or KHS seems to contain no oxidizing agent of anywhere near sufficient strength. (In most of the experimental work atmospheric oxygen was rigorously excluded.) The strongest oxidizing substance present is HS^-, which would have to react according to the equation

$$Au + HS^- = AuS^- + \tfrac{1}{2}H_2 \qquad (23)$$

This seems patently absurd; a metal immune to attack by strong acids should be completely indifferent to a very weak acid like HS^-. The only possibility is that AuS^- may be exceptionally stable, sufficiently so to pull the reaction to the right in spite of the weakness of HS^-. If we make this assumption, it is possible to get a measure of the stability of AuS^- from the solubilities found by Ogryzlo and by Zvyagintsev and Paulsen. The data

are not entirely consistent, but suggest a solubility of about 0.0001 mole/liter of AuS^- in 2M HS^- at room temperature. This gives an equilibrium constant for equation 23 of about 10^{-6}, which leads to ΔF° = ca. + 8,000 cal. Using +3,000 cal as the free energy of formation of HS^-, we find for the free energy of formation of AuS^-, ΔF° = ca. +11,000 cal.

With this figure we can compare the stabilities of AuO_2^- and AuS^- by calculating the free energy changes in the reactions

$$2HS^- + AuO_2^- = AuS^- + S + 2OH^-$$
$$2H_2O + 2S^{--} + AuO_2^- = AuS^- + S + 4OH^-$$

for which ΔF° = ca. −54,000 and −71,000 cal, respectively. The high negative values mean that AuS^- is very much more stable than AuO_2^-, so that an alkaline solution containing even a trace of sulfide must have its dissolved gold in the form of AuS^-.

The extent of solubility of gold as AuS^- at ordinary temperatures can be estimated from the approximate value of K, 10^{-6}, derived for equation 23. If no hydrogen is present from any other source, the solubility is $1.3 \times 10^{-4} \times (HS^-)^{2/3}$, which means that it is appreciable (ca. 3×10^{-6} gram/liter) even at HS^- concentrations as low as 10^{-6} M.

As Smith (2) has pointed out, the fact that gold itself will not dissolve in solutions of S^{--} does not mean that gold cannot be carried in such solutions. The solubility of gold sulfide in excess sulfide suggests that transportation in this manner is possible, but no quantitative data are available.

In summary, gold can be carried in alkaline solutions as AuO_2^- if sulfide is absent or as a complex sulfide ion if sulfide is present. The most probable complex sulfide is AuS^-, which appears to form from metallic gold in solutions of HS^- but not in solutions of S^{--}. A possible interpretation of the solubility of gold in HS^- is that the ion AuS^- is extraordinarily stable, so stable that the hydrogen of HS^- is reduced to H_2. If this interpretation is correct, significant amounts of gold should be held in solution even by dilute, approximately neutral solutions of HS^-. Naturally-occurring alkaline solutions do not affect metallic gold appreciably in the absence of HS^-.

SOLUBILITY OF GOLD IN SEA WATER.

In sea water, which is a slightly alkaline solution without appreciable sulfide ion, the solubility of gold is very small. A rough value can be calculated from equation 22 and a similar equation involving $AuCl_4^-$:

$$2Au + 3/2O_2 + 2OH^- = 2AuO_2^- + H_2O \qquad (22)$$
$$2Au + 3/2O_2 + 8Cl^- + 3H_2O = 2AuCl_4^- + 6OH^- \qquad (24)$$

For equation 22 we have obtained an equilibrium constant equal to ca. 10^{-10}; for equation 24 the constant (calculated from electrode reactions 5 and 14) is 10^{-60}. In sea water of normal salinity the concentration of Cl^- is about 0.55M, and for water in contact with air we may take the partial pressure of O_2 as 0.2 atmos. The pH of sea water ranges from about 7.5

TABLE VI.

CALCULATED SOLUBILITIES OF GOLD IN SEA WATER AT 25° C. IN CONTACT WITH AIR (IN MOLE/LITER).

pH	OH^-	$AuCl_4^-$	AuO_2^-	Total Au
7	10^{-7}	3×10^{-11}	3×10^{-13}	3×10^{-11}
7.5	$10^{-6.5}$	10^{-12}	10^{-12}	2×10^{-12}
8	10^{-6}	3×10^{-14}	3×10^{-12}	3×10^{-12}
8.5	$10^{-5.5}$	10^{-15}	10^{-11}	10^{-11}

to 8.4, so that the OH^- range is between $10^{-5.6}$ and $10^{-6.5}$ mole/liter. Calculations covering this range give the figures shown in Table VI.

Such calculations are not to be taken too seriously, since in solutions as concentrated as sea water the activities of ions are markedly different from their concentrations; the values in Table VI may well be in error by one or two orders of magnitude. Nevertheless, these calculated figures bear a striking resemblance to Haber's (14) experimentally determined value, 2×10^{-11} mole/liter. A possible interpretation is that sea water obtains its gold largely by dissolving the native metal with the aid of oxygen, and that the amount in solution is limited by the equilibria in equations 22 and 24.

EFFECT OF TEMPERATURE AND PRESSURE.

The effects of temperature and pressure on the solubility of gold are not predictable because thermodynamic data are lacking. Experimentally McCaughey (9) showed that the solubility in solutions containing Fe^{+++} and Cu^{++} is increased by a rise in temperature, although some of the apparent increase may be due to higher reaction rates rather than to shifts of equilibrium. Ogryzlo's work (1) with solutions in bombs at 200°–300° C indicates that oxidation by free oxygen goes farther at high temperatures, but again the apparent increase may reflect chiefly a speeding up of the reaction. Ogryzlo shows further that even the reaction with HCl alone, with no oxidizing agent present stronger than H^+, becomes appreciable at high temperatures and pressures. In alkaline sulfide solutions the experiments of Ogryzlo and of Zvyagintsev and Paulsen (3) demonstrate a marked increase in solubility at high temperatures—showing that gold differs in this respect from mercury, whose complex sulfide ion becomes less stable as the temperature rises. Any gold solution, therefore, appears able to hold more gold at high temperatures than at low temperatures, so that simple cooling provides an adequate mechanism for the deposition of the metal from vein solutions.

The effect of pressure, as distinct from temperature, has not been investigated experimentally. The effect is probably negligible on the reactions which do not involve a gas (e.g., equations 19 and 20), but may be large if a gas is produced or consumed. Reactions requiring both H^+ and Cl^- (equations 17 and 18) would necessarily be aided by increased pressure at high temperatures, since the pressure determines how much HCl will

remain in solution. The direct solution of gold by HCl alone at high temperatures (1) must likewise depend on pressure. In neutral or slightly alkaline solutions the solubility of gold as AuS^- should depend on pressure insofar as pressure determines the solubility of H_2S and hence the concentration of HS^-. From such general considerations it appears that in most solutions gold is more soluble at high pressures than at low pressures, and accordingly can be precipitated by release of pressure.

COLLOIDAL SOLUTIONS.

Frondel (15) has shown that gold sols, especially when protected by colloidal silica, are stable at high temperatures. If gold originally present in true solution at high temperatures is reduced to the metal as the temperature falls, it may well appear first as a colloid rather than as a precipitate, and in this form may be transported in quantities larger than would be expected in true solution. The common association of gold with sulfides is explained by Zvyagintsev and Paulsen (16) as a surface effect of the sulfides on gold sols, since their experiments show that gold coagulates more readily on sulfides than on quartz, calcite, or barite.

SUMMARY.

1. Solubilities of gold calculated from thermodynamic data agree reasonably well with experimental results.

2. In acid solutions gold may be transported as the ion $AuCl_4^-$, provided that reducing agents are absent. The metal is dissolved by an acid solution provided that the solution contains Cl^- and that a fairly strong oxidizing agent is present. At high temperatures and pressures the hydrogen ion of the acid is a sufficiently strong oxidizing agent; at low temperatures a substance like MnO_2, O_2, Fe^{+++}, or Cu^{++} must be present in addition. The requirement that an oxidizing agent be present, or at least that a reducing agent be absent, probably means that gold would not be transported in acid vein solutions at low temperatures, since such solutions would contain reducing agents like H_2S and Fe^{++}. On the other hand, solution and transportation of gold in acid solution is probably the mechanism of supergene movement of gold.

3. The solubility of gold in naturally-occurring alkaline solutions which do not contain sulfide is negligible.

4. Gold may be transported in alkaline sulfide solutions, even in dilute solutions near the neutral point. The gold is probably present as the very stable ion AuS^-.

5. Gold may be precipitated from solution by any one of a number of mechanisms, but there is no need to call on one more complicated than a fall in temperature or pressure or both.

6. If a solution of gold at high temperature and pressure is cooled, part of the metal may be forced out of solution but may appear as a sol rather than as a precipitate. In this form it may remain in suspension down to low temperatures.

7. Because gold may be transported in solutions of various compositions, the presence of gold in a vein deposit gives little information as to the character of the vein fluids.

8. In sea water gold is probably present as both AuO_2^- and $AuCl_4^-$. A limit to the amount dissolved may be set by the formation of these ions from metallic gold with the aid of dissolved oxygen.

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THE INFLUENCE OF PERMEABILITY ON ORE DISTRIBUTION IN LIMESTONE AND DOLOMITE.[1]

ERNEST L. OHLE.

PART II.

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GEOLOGY OF THE MASCOT-JEFFERSON CITY, TENNESSEE, ZINC DISTRICT.

The Mascot-Jefferson City, Tennessee, Zinc District is located in the Valley and Ridge province. It extends in a northeasterly direction for 20 miles from a point ten miles northeast of Knoxville. Mines are located at Mascot, New Market, and Jefferson City. New Market is four miles southwest of Jefferson City. All of these places are on the Maynardville Quadrangle and are shown on the District Map, Figure 18.

This district is the most important part of a much larger area, comprising practically the entire Great Valley of Tennessee, in which zinc mineralization occurs in varying degrees of concentration. Important mines are also located at Austinville, in southwestern Virginia, but the ore there occurs approximately 7,000 feet stratigraphically below the position of the principal deposits in Tennessee. The present production in the Mascot-Jefferson City district by the American Zinc Company of Tennessee and the Universal Exploration Company is about 4,000 tons per day of 2½ to 6 percent zinc ore.

[1] This is paper No. 126 published under the auspices of the Committee on Experimental Geology and the Division of Geological Sciences at Harvard University. It was presented before the Washington meeting of the Geological Society of America in November, 1950.

The geology of the Appalachian Valley in Tennessee in general and of the zinc deposits in particular has been described by many authors. Safford [76] and Keith [77] made early studies of the region. In more recent years Bridge [78] and Oder [79] have added details to our knowledge of the stratigraphy and structure. The Knox dolomite, with an approximate thickness of 3,000 feet, has been subdivided into five formations and the description of these units is mapped in the vicinity of the zinc deposits and elsewhere in the Valley.

Very detailed descriptions of the stratigraphic sections exposed within the mines at Mascot, New Market, and Jefferson City have been published by

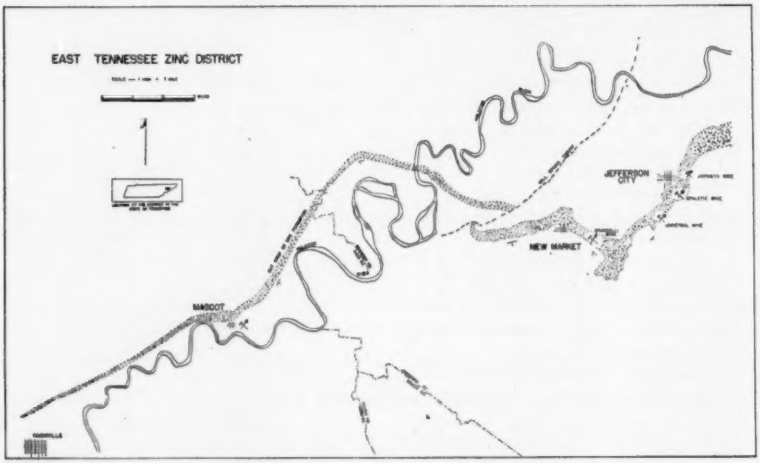

FIG. 18. Map of the East Tennessee Zinc District showing the location of the mines and the outcrop of the ore formation (dotted area).

Oder and Miller.[80] Brokaw and Jones [81] and Crawford [82] have described the structures which control the ore in certain mines and stopes. A recent paper by Oder and Hook [83] is the best general description of the mineral occurrences in the producing district. For descriptions of the many outlying zinc show-

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[81] Brokaw, A. L., and Jones, Charles, Structural control of ore bodies in the Jefferson City area, Tennessee: ECON. GEOL., vol. 41, pp. 160–165, 1946.

[82] Crawford, Johnson, Structural and stratigraphic control of zinc deposits in East Tennessee: ECON. GEOL., vol. 40, no. 6, pp. 408–415, 1945.

[83] Oder, Charles R. L., and Hook, John W., Zinc deposits of the southeastern states *in* Symposium on mineral resources of the southeastern United States, The University of Tennessee Press, Knoxville, 1950.

ings up and down the Valley from the main area, reference should be made to Secrist.[84]

The ore occurrences in the Mascot-Jefferson City area are found in folded and faulted limestones and dolomites of Lower Ordovician age; they are confined to the lower Kingsport and upper Longview formations and thus lie in the lower half of the upper third of the Knox group. As indicated in the stratigraphic section published by Oder and Miller, the upper 200 feet of the mine stratigraphic section is predominately light to dark gray, dense dolomite with some thin, interbedded brown limestone layers. Underlying this unit is approximately 150 feet which is largely limestone but which contains a number of thin, light to dark gray, dolomite beds.

A spectacular feature of the East Tennessee zinc ore bodies is the widespread brecciation of the fine-grained dolomite layers. Breccia fragments are of all sizes up to several feet across. They are sharply angular. Many of them have the domino breccia shape usually described as a result of "extensional stress" (Fig. 19). As several of the beds which are most often brecciated are black, there is a sharp color contrast between the fragments and the white dolomite or yellow sphalerite which make up the cementing matrix.

Within and near ore bodies, the limestone beds are recrystallized and dolomitized to a coarse, dolomitic marble locally termed "recrystalline" (Fig. 20). There is a halo of this "recrystallized" limestone of varying width around all ore bodies, the alteration having spread laterally from zones of deformation. Bedding planes are the avenues most often used for lateral migration of the solutions and it is common to see a 5–6 foot "recrystalline" layer give way by gradual tapering to unaltered rock at the edge of an ore body. The upper contact of the bed is the last part to pass into limestone. Or, to put the events in their natural sequence, as "recrystallization" proceeds, it works its way outward along the top bedding plane of the limestone layer. Very often the bed above is a dense, fine-grained dolomite. As the sharp edge of the wedge advances into unaltered rock, a greater and greater thickness of the original bed is effected until, finally, if the process goes on long enough, the total bed thickness has been altered. Figure 21 is an idealized cross-section of the edging out of "recrystalline" halo. The angle of taper of the wedge may be acute or may approach 90 degrees. In the latter instance the influence of the top and bottom contacts of the limestone is about equal and "recrystallization" appears to proceed as an altering wave.

In many places the "recrystallization front" is far in advance of mineralization so that the halo is wide. Quite commonly, however, and especially in U-bed, the halo is narrow and a high percentage of the altered rock is ore. It is frequently the case that the thin edge of an ore body as it tapers out is of higher grade than the thicker main portion.

In some places where the change from limestone to "recrystalline" takes place over a distance of a few feet, the most advanced phase of alteration is the development of scattered "eyes" of coarse (+ .5 millimeter) dolomite in the fine (.01 millimeter) limestone. Figure 22 illustrates this stage in the

[84] Secrist, Mark, Zinc deposits of East Tennessee: Tenn. Div. Geology Bull. 31, 1924.

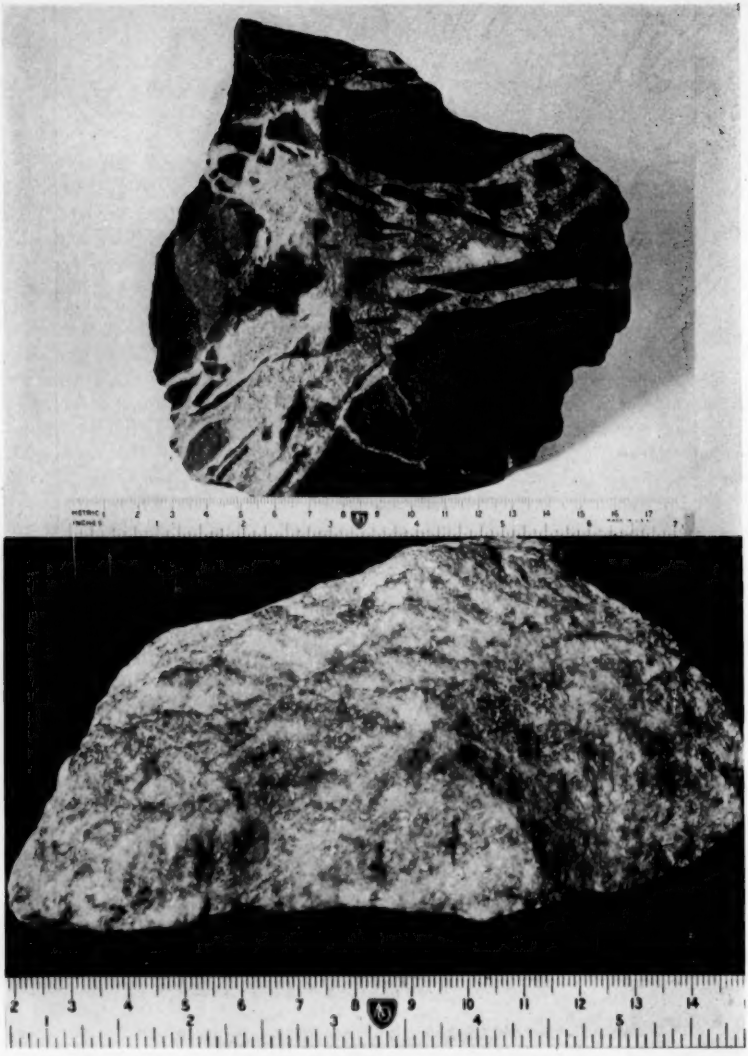

FIG. 19. (Upper.) Brecciated G-27 bed from Grasselli Mine, New Market, Tennessee. The brecciation is of the type often called "extensional." The white gangue is dolomite. Sphalerite (Sl) tends to favor the top side of the fragments as found in place. This specimen is inverted in the photograph.

FIG. 20. Coarse "recrystalline" dolomite from G-10-17 bed at Grasselli Mine. The dark streaks may be remnants of stylolites which were present in the limestone before "recrystallization." One-eighth-inch bands of sphalerite adjoin many of these streaks but are difficult to distinguish in the photograph. Sphalerite also occurs in disseminated grains. Ten feet from the original location of this rock, the bed was limestone.

process. "Pure recrystalline" develops as the large dolomite grains become more and more abundant.

Stylolitic seams in the limestone are favored avenues for the migration of altering solutions and wavy seams of "recrystalline" work their way through limestone along stylolites from which they spread laterally. The process as it occurs in U-bed is illustrated in Figure 1. Complete "recrystallization" usually destroys the argillaceous stylolites so that short, disconnected segments of the seams are all that remain in well "recrystallized" rock.

The widespread persistence of minor units in the mine stratigraphic column is truly remarkable. The features of the formation are well known from study of several hundred miles of mine workings, drill cores, road cuts, and other exposures. Oder and Miller present detailed stratigraphic columns for

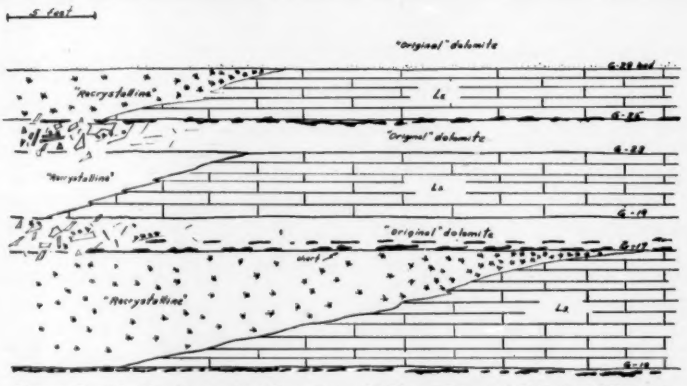

Figure 21. Idealized cross-section of ore (?-?) and "recrystalline" wedging out at the edge of an ore body. "Recrystalline" extends laterally beyond strong brecciation in "original" dolomite (plain) but eventually passes into limestone. Ore commonly is very rich in the tapering "recrystalline" wedge.

FIG. 21.

Mascot, New Market, and Jefferson City. Many minor features, such as 4–6-inch sandy beds, 2–3-foot layers of dark dolomite, layers with distinctive spotting or banding and chert beds with characteristic color or structure can be singled out of all three sections, though Mascot is 18 miles from Jefferson City. Certain variations occur, especially in the thickness of the main limestone sections, but in general the same stratigraphic column could be used at all three places. Some of the thicker units, such as the J–13–60 limestone, have been found in surface exposures 65 miles to the northeast, and the chert matrix sandstone, which is rarely over one foot thick at the top of the Kingsport, has been found along the outcrop for well over 100 miles. It is not unlikely that, if continuous exposures were available everywhere such as are presented in the mine openings of the zinc district, many of the minor features could also be shown to exist over these considerable distances.

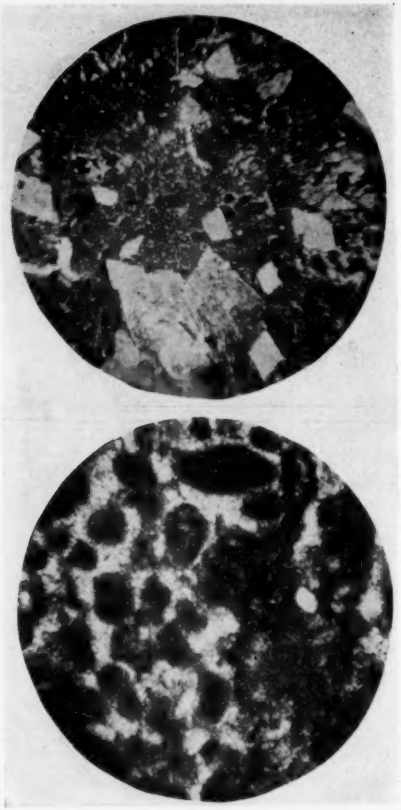

FIG. 22. (Upper.) Cloudy, fine grained, U-bed limestone being replaced by scattered, coarse "birds-eyes" of dolomite. ET-23, Athletic Mine, × 15.

FIG. 23. (Lower.) U-bed limestone from Jarnagin Mine showing the oval-shaped clusters of fine grained, much clouded calcite grains, separated by a coarser grained, clear matrix. ET-13, × 15.

The very complete knowledge of the stratigraphy in the ore-bearing section is one of the features which makes the East Tennessee district attractive for a study of rock properties and their relation to ore. An excellent opportunity is presented here also for a study of the effect of the mineralizing solutions on different rock types, i.e., wall rock alteration. Not all of the beds have reacted alike either to the ore solutions or to the tectonic forces which created the structurally "prepared ground." Some beds, notably the limestones which "recrystallize," lose entirely their original character and appearance.

Fortunately other adjoining beds retain their customary appearance through all the flexures and zones of fracturing so that it is possible almost without exception to tell one's exact stratigraphic location at all times.

The published mine stratigraphic column indicates the stratigraphic position of the most favorable ore zones. It is at once apparent that the bulk of the production is from the lower zone of interbedded limestones and dolomites, although a substantial amount of ore is mined from the dolomites of the upper zone. The upper-zone ore is largely open space filling in which sphalerite and gangue dolomite form the matrix of brecciated and crackled dolomite. Replacement is of secondary importance and is concentrated in the few limestone beds in this zone. In the lower zone, replacement predominates and open space filling is of secondary importance. Replacement ore is usually of better grade and greater lateral extent than breccia ore. The grade of breccia ore, by the very nature of things, is related to the size and number of the open spaces; it is rich near centers of extreme fracturing and trails off to assay walls as the intensity of shattering decreases. Thus it is inclined to be pockety and erratic.

The relationship between grade and type of ore and original character of the individual rock layers can be carried even farther than the above generalization. Constant association with the ore bodies promotes a familiarity with the eccentricities of each of the units in the rock section. The spacing of prospect holes deemed advisable and the location of mine developments are varied accordingly. Thus there is much greater confidence that an ore body in a "recrystallized" limestone bed, such as U-bed, will mine with a grade closely approximating that anticipated from the drilling than there is for an ore body in brecciated "original" dolomite. In the latter case the ore is erratic and there is a much greater risk factor.

Although the main ore trends are invariably lines of structural deformation, there are certain limestone beds within which the ore solution has spread laterally into adjacent unbroken ground. Figure 24 is a somewhat generalized sketch of a stope in the Jefferson City area in which the ore followed the limestone just below the J–139 bed for over 100 feet outward from a zone of intense deformation. The halo of "recrystalline" spread farther in this layer than in any of the other limestones cut in the stope. In this J–137–139 bed the ore was rich enough to pay for mining the necessary eight-foot thickness. The beds above and below were unbroken and ore seems to have been localized in this particular unit because the solutions migrated outward along the J–139 bedding plane and the "recrystallized" limestone more readily than along the adjacent beds.

Similar occurrences involving the J–137–139 bed (G–49–50 bed) are found in the Grasselli Mine at New Market. Other limestone beds which are particularly favorable are the G–10–17 bed and the J–3 to (–13) bed (also known as M–(–16) to (–23), G–(–76) to (–88), or U-bed). In the case of the latter, narrow ore trends 1,500 to 2,000 feet long have followed almost imperceptible flexures or simple fractures from which the ore solutions spread laterally through the rock. No other bed contains minable ore related

to such subtle structures and this layer is adjudged to be the most hospitable rock in the district.

Individual stopes and ore trends occur in zones of warping and attendant shattering. Faults and fractures do not directly control the ore but undoubtedly they are more numerous in ore-bearing areas. Ore bodies often end against fractures but sometimes the mineralization improves on the "other" side of the fracture. Faults and fractures are not so mineralized as to constitute veins, even though many are known to be pre-ore.

Much more important, ore-wise, than the fractures are zones of "domino" breccia developed by shattering and slabbing of the rocks during flexing. Locally intense solution and removal of certain limestone layers and con-

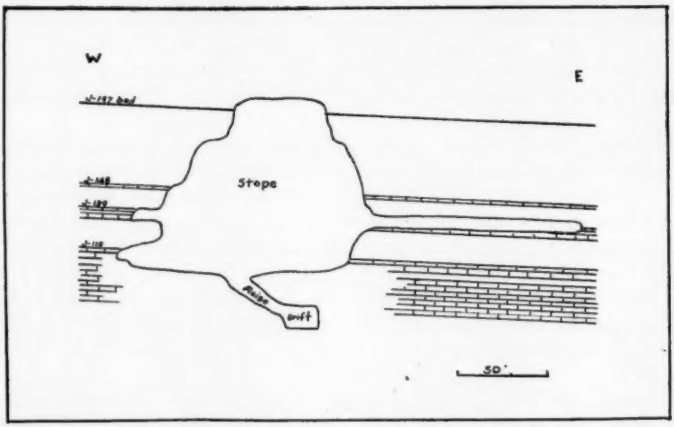

FIG. 24. A generalized cross-section of a mined ore body in the Jefferson City area. The high ore occurred in a through-going zone of shattering from which a thin streak spread laterally in the limestone just below the J-139 bed. The rocks not shown as limestone are fine grained dolomite, or, in the case of limestone beds where altered, "recrystalline."

sequently withdrawal of support for the overlying beds may have been a contributory factor in the development of the breccia. Generally these zones are elongate so that the ore occurs in "trends." Bedding plane movement played an important part in the deformation. Several parallel flexures may be present in an ore trend 200–300 feet wide. The shattering of the beds was not such as to mix up completely fragments of the various rock layers. Generally the individual pieces are fairly close to their original neighbors and it is possible to match adjacent blocks together. Distinct zones containing fragments of the various layers can be traced from unfractured wall to unfractured wall, although not an undisturbed bedding plane exists between the sides of the ore body.

These brecciated zones at one time had an enormous amount of open space and they offered good avenues for the circulation of the ore solutions. In

some places the fracturing affected 10 feet of beds; elsewhere it involved 125 feet or more. Most ore trends have a certain degree of consistency as to thickness. The overlying and underlying beds, especially the former, commonly are not brecciated and, together with the unbroken walls, constitute a relatively impermeable lining to the ore channelways. The cap rock and, in many stopes, the floor rock are dense dolomites, competent under the prevailing conditions and also non-reactive to the "recrystallizing" solutions. In the walls of the channelway there were usually some limestone layers which, by altering to coarse grained dolomite, became more permeable and thus, to a small degree, tended to enlarge the carrying capacity to the channelway. A further elaboration of this effect of "recrystallization" on permeability will be found below.

A remarkable feature of these zinc deposits, in the light of the large amount of open space which once existed in the brecciated trends, is the almost complete absence of vugs or openings of any kind at the present time. Gangue dolomite, a little calcite, and the sulphide minerals entirely filled the existing space. Even fine hair-like cracks that seem to "dead-end" in dense rocks are filled.

RESULTS OF PERMEABILITY TESTS ON EAST TENNESSEE ROCKS.

Location of the Samples.

Samples were collected in the Jarnagin, Athletic, Universal, and Grasselli Mines. The locations of these properties are shown on the district map (Fig. 18). From the farthest northeast point in the Jarnagin Mine to the southwestern extremity of Grasselli Mine is four airline miles or five miles along the strike of the formations.

Practically all of the samples came from three short sections in the stratigraphic column: the Jarnagin 130–139 zone (known at Grasselli as the 43–50 zone); the Jarnagin 97–104 zone (Grasselli 10–17); and the Jarnagin 3 to (–13) zone (Grasselli (–76) to (–88) or, according to the Universal Mine system, U-bed). These sections were selected because their limestone portions have proved to be the most favorable parts of the formation for lateral spreading of replacement ore. In zones of intense fracturing in which great thicknesses of formation are mineralized, these beds usually carry the highest grade of ore; in the very weakly deformed or even undeformed areas lying adjacent to the strong, through-going structures, there often is no mineralization at all except in one or more of these beds. Ore only five to fifteen feet thick vertically may spread laterally for several hundred feet from the major ore trend; U-bed shoots 10 feet thick and 100–200 feet wide have extended as much as 2,000 feet from brecciated chimneys which cross-cut great thicknesses of formation. Often the bulk of the ore in U-bed is concentrated in the top four feet.

In order to test whether permeability was an important factor in the location of the ore in these particular thin limestones, samples were taken of the beds overlying and underlying the ore as well as of the ore-bearing layers themselves. In most places the overlying bed is a fine grained "original" dolomite; the underlying bed occasionally is dolomite but perhaps more often,

and especially at the edges of ore bodies, it is unaltered limestone. In an attempt to duplicate the relative permeabilities of the beds as they were when first presented to the dolomitizing solutions as potential avenues of circulation, many of the samples were selected in locations where the beds were as nearly as possible in their original condition. The "recrystalline" halo around some ore bodies is so narrow that samples of essentially unaltered limestone can be found in stope walls.

As it seemed probable that pre-sulphide rock alteration from limestone to dolomite might have an important effect on permeability, suites of samples were taken across alteration contacts. In the U-bed ore zone in 2-North stope at Jarnagin Mine, for example, the rock changes progressively over about 20 feet from coarse grained "recrystalline" dolomite to partially altered limestone and thence to practically unaltered limestone. Samples were selected at intervals to test the relative permeability of the several stages. Samples of ore-bearing "recrystalline" were taken also so that the effect of sulphide deposition could be measured.

In order to check the mine samples for possible blasting effects, cores were taken from three diamond drill holes located several thousand feet from the workings. One hole was located approximately 2,400 feet due west of the Grasselli No. 1 shaft (just east of the numeral "2" on Bridge's district map). The rock in this hole was much brecciated and the hole cut ore just below the Grasselli-17 bed.

Since it was possible that macroscopically unnoticeable rock alteration in the vicinity of the ore bodies might affect the permeability measurements, it was thought desirable to sample the beds in an area that was far removed from known ore, and, if possible, completely unaltered. For this purpose the Jarnagin No. 1 hole was chosen. It lies approximately 2,500 feet southeast of Jarnagin shaft and 1,200 feet from the nearest workings. It is essentially a "lime" hole.

The Jarnagin No. 2 hole location is 1,200 feet southeast of the mine shaft and 1,000 feet east of the closest workings. This hole and the Grasselli hole are directly down-dip from mine stopes.

A total of 48 mine specimens and 21 sections of diamond drill core were collected for laboratory measurement. From these 146 test discs were cut.

The Rock Types and Their Permeabilities.

At the outset of this study it was thought that there might be a correlation between ore distribution and the permeability of the individual rock layers. If it could be shown that, at the time the ore solutions moved through the rock section, certain beds presented potential avenues of circulation many times more efficient than neighboring beds and that these same beds most often were mineralized, then the possible influence of permeability would be demonstrated. Conversely, if the correlation were negative, it would be shown that some other rock property or some structure controlled the circulation of the ore fluid.

As the experiments progressed, it became apparent that, instead of there being specific and significant permeability values for each of the layers, there were three main groups of permeability values which corresponded to the three main rock types: limestone, "recrystalline," and "original" dolomite. All of the rocks measured fell into one of these three types and it is almost certain that tests of each individual layer in the 200-foot rock section exposed in the mines would show the three-fold division to be valid for the entire group. There was no measurable variation in the permeabilities of the individual beds or rock types from mine to mine or in the drill holes. Neither mine blasting nor the method of cutting the specimen from the hand specimens seemed to have any appreciable effect on the results.

Recognition that there were three rock types with rather well defined limits of permeability instead of a considerable number of individual beds with characteristic K values somewhat altered the original objective, especially so since one of the rock types was a secondary alteration product. The process whereby "recrystalline" was formed from limestone and particularly the time relations between "recrystallization" and sulphide introduction became matters of great significance. Since suites of samples had been collected across alteration contacts, it was possible to measure the variation in permeability as the limestone became progressively more altered.

"Original" Dolomite.—The "original" dolomites are uniform, dense, fine grained rocks occurring in beds a few inches to several feet thick. The thicknesses of the various beds are remarkably constant. The layers range in color from nearly white to black. Upon flexing they have shattered and given rise to "domino" breccia but in many stopes the ore is overlain by an unbroken bed of dolomite. Stylolites are uncommon although the beds are nearly pure calcium magnesium carbonate of nearly perfect dolomite composition. In rare specimens the grain size reaches .1 mm (sugary) but the average is about .02 mm.

Seventeen specimens were selected as representative of the "original" dolomites in the mine stratigraphic section. These specimens came from T-bed (six specimens), Footwall (two), Jarnagin 139-bed (three), Jarnagin 134–138-bed (two), Jarnagin 103–104-bed (one), Grasselli 104-bed (one), Grasselli 39-bed (one) and Jarnagin 120-bed (one). The permeability of the 17 specimens ranged from 5.8×10^{-4} millidarcies to 3.1×10^{-6} millidarcies; the average value was 8.1×10^{-5} millidarcies. The six specimens from T-bed averaged 9.8×10^{-5} millidarcies while the Jarnagin 139-bed specimens averaged 3.5×10^{-5} millidarcies and the Footwall specimens averaged 1.5×10^{-5} millidarcies.

All of the discs were unfractured and stylolites were very uncommon as in the rock in place. Obviously this rock type is very dense when unbroken. The brecciated zones which developed when the brittle rocks were subjected to stress, however, were the main avenues of ore solution circulation throughout the district. All important ore bodies are associated with the brecciated shoots although not all the ore is in breccia.

Limestone-"Recrystalline."—The limestones are dense and fine grained with an average grain size of about .01 millimeter. Their fracture is sub-

conchoidal. In the mine they are brown in color but on weathered outcrops they are dove gray. Stylolites are common and it is not uncommon to find a six-inch layer suddenly become riddled with tiny stylolitic seams and finally pass laterally into a ½-inch greenish shale residue. Some layers have a great susceptibility to solution in this way; in the case of the limestone just

FIG. 25. Sharp contact of brown limestone (lower part) and coarse "recrystalline" dolomite in the 132-4 bed at Jarnagin Mine. Sphalerite is restricted to the coarse dolomite except for tiny disseminated specks in the limestone within a few inches of the contact.

beneath the Grasselli 50-bed, the bed that is the parent of the thin green shale seam is rarely found.

The carbonate portion of the unaltered limestone is practically pure calcite as shown by the analysis of specimen 13 (Table 1). Under the microscope the grains are much clouded by fine "dust" which never has been satisfactorily

identified but is probably clay. In some sections the cloudy material is clustered in oval shapes resembling oolites (Fig. 23). Seemingly this cloudy material is the insoluble residue which collects along stylolitic seams. Replacement of cloudy limestone by coarse dolomite tends to clear up the cloudy condition but occasionally the nearly opaque concentrations are retained in completely altered rock.

FIG. 26. Coarse dolomite veinlet crossing dense, cloudy limestone. The lighter gray, shadowy, central portion of the veinlet may indicate the location of a once-open crack from which the dolomitization proceded to attack the limestone. The dolomite in the veinlet exhibits wavy extinction. Jarnagin Mine, × 16.

The "recrystalline" beds are fine to coarse dolomitic marble into which the limestone layers are altered—especially in the vicinity of ore bodies. The grains range in size from .2 to 1.5 mm and average about one mm. The transition from limestone to "recrystalline" may be practically a knife-edge as in Figure 25 but more commonly the change takes place over a distance

of a few inches to several feet. In thin section, veinlets of coarse dolomite can be seen to be working into the unaltered limestone (Fig. 26). Often the alteration moves along stylolites but sometimes it ignores these structures, which possibly are post-alteration but may simply have been sealed off by the residue at the critical time. In other places the alteration to "recrystalline" takes place through the growth of isolated grains and patches of dolomite within the limestone, the patches being progressively smaller and less numerous outward from the replacement "front." By continued growth and coalescence of the dolomite "centers," the rock is completely transformed. In still a third method of attack, the dolomitization works outward from a well defined crack through the limestone. Figures 27–A and 27–B show a specimen of partially "recrystallized" limestone before and after staining with ferric chloride and ammonium polysulphide; the dolomite is replacing limestone along cracks and in isolated areas.[85]

Most "recrystalline" is light to dark gray in color though some has a brownish caste. It is a massive rock and approaches theoretical dolomite in composition. An even mixture of light and dark grains results in a "salt and pepper" appearance. Well crystallized white gangue dolomite may be present as a dissemination or in irregular areas and fracture fillings. Often it comprises as much as 50 percent of the rock. Very dark "recrystalline" usually contains a high percentage of black jasperoid and is harder than ordinary types.

Upon total "recrystallization" the stylolites in the limestone are destroyed and short, disconnected black streaks are all that is left of the green or black residue seams.

Completely altered limestone is almost invariably coarse. Partially altered rocks with both coarse and fine grained areas are common. The fine sugary-textured "recrystalline" which is an occasional alteration product is not favorable for replacement by ore but may have ore in fractures if the bed has been broken. Normally the sphalerite in "recrystalline" ore has replaced carbonate by attacking scattering dolomite grains, thus giving rise to disseminated ore. If jasperoid has previously attacked the carbonate, the sulphide preferentially attacks the jasperoid. In some sections, as much as 35 percent of the rock is jasperoid which is generally fine-grained and dark olive in color. In partially silicified rocks the jasperoid is distributed in nests of tiny (.005–.01 mm) grains scattered through the carbonate. Some of the secondary silica is in the form of tiny (.08 mm) quartz grains. Sections of highly silicified rock always appear "dirty." Silicification tends to follow stylolitic seams.

An interesting feature of most of the coarse dolomite grains is their "wavy extinction." In one thin section the cleavage cracks also appear warped. These observations are discussed further in the discussion of the origin of "recrystalline" on pages 887 and 891.

Although most of the dolomite grains are "cleaner" than the grains in the original limestone, there are many examples of cloudiness in coarse altered

[85] This staining technique is described in Fairbairn, H. W., Structural petrology of deformed rocks, p. 31, Addison-Wesley Press, Cambridge, Mass., 1942.

FIG. 27A. Partially altered limestone from Athletic Mine.
FIG. 27B. Same specimen as 27A after staining with ferric chloride and ammonium polysulphide which darkens the limestone portions.

rock. Generally the clouding material is the same fine clay-like material seen in the limestone; other inclusions are tiny, rhombohedral grains which may be calcite that resisted dolomitization and were incorporated during the growth of the coarse grains. Their size prevents more accurate identification. Other tiny "inclusions" may be fine silica—the advance attack in alteration of carbonate to jasperoid.

Banded "recrystalline" rocks in which one-eighth to one-half inch layers of light and dark gray color alternate are seen in thin section to consist of layers of different grain sizes. The coarse-grained layers appear as light bands while the smaller grain sizes appear dark.

Probably no specimens were collected that were completely devoid of dolomite. In several specimens which were assayed, however, over 95 percent of the contained carbonate was calcite. These are shown in Table 1 (Specimens 13, 43–2, 47–2, and 90) and suffice to indicate the relative impermeability of the original unaltered limestone. The analyses indicate a normal amount of insoluble material for this type of rock. Specimen 43–2, which has the highest insoluble analysis, was cut by a green stylolite .6 mm wide; specimen 90 contained several extremely thin stylolites.

Eleven limestone specimens, including the four noted above, were selected as approximating their original character. Probably none of them was over 10 percent dolomitized. Of the eleven, five came from U-bed, three from Jarnagin 132–134 zone, and three from Jarnagin 100–103 zone. The eleven gave a range of permeability from 1.6×10^{-4} millidarcies to 2.5×10^{-7} millidarcies while the average value was 2.7×10^{-5} millidarcies. The mode was 2.2×10^{-5} millidarcies. The U-bed specimens gave an average value of $5. \times 10^{-6}$ millidarcies while the J–132–134 and J–100–103 zones gave values of 3.6×10^{-6} and 5.3×10^{-5} millidarcies, respectively. The unaltered limestones thus are slightly less permeable than the original dolomites on both extremes and in the average.

The alteration of limestone to "recrystalline" is a progressive change in which the calcite is converted to dolomite and the grain size is much increased. Alteration in all probability is never complete. Hence, it is difficult to select "pure" type examples. Since only a few specimens were analysed, in the majority of cases the specimens selected had to be chosen because they appeared to be "good" "recrystalline." Among the specimens actually analysed, there were three in which over 88 percent of the carbonate was dolomite (Table 1, specimens 33–1, 48–2, and 93).

Eighteen "recrystalline" samples were chosen from U-bed (seven samples), J–100–103 zone (five), J–132–134 zone (four), Grasselli 27 bed (one), and J–20 bed (one). Their permeabilities ranged from 4.5×10^{-5} millidarcies to 3.9×10^{-2} millidarcies and their average permeability was 4.9×10^{-3} millidarcies. The mode of these values was 9.3×10^{-4} millidarcies. However, the three lowest values were from specimens found to contain large amounts of jasperoid.[86] Leaving out these samples the average becomes

[86] Specimen 44–1 was one of those with high jasperoid content. Table 1 indicates that it had an insoluble content of 21.3 percent.

5.9×10^{-3} millidarcies, the minimum value 1.7×10^{-4} millidarcies and the mode 1.3×10^{-3} millidarcies. The U-bed samples averaged 8.9×10^{-3} millidarcies and the J–100–103 and J–132–134 zone specimens, omitting those containing much jasperoid, averaged 8.6×10^{-4} and 3.5×10^{-3} millidarcies, respectively.

It is obvious that the permeability of the limestone layers is tremendously increased by "recrystallization." The average increase indicated here is over 18,000 percent and, if completely unaltered limestone could be taken on the one hand and its completely altered equivalent on the other, the percentage increase in permeability would be much greater. U-bed limestone from Jarnagin diamond drill hole No. 1 (in a virtually unaltered area) gave a permeability test of 1.8×10^{-6} millidarcies; U-bed 93 percent altered to dolomite (specimen 33, taken within 10 feet of ore in the Universal Mine) returned 3.9×10^{-2} millidarcies. The "recrystalline" is over 20,000 times (2,000,000 percent) more permeable than the limestone. "Recrystalline" so completely dominated the field insofar as intergranular flow is concerned that it will be discussed in greater detail.

Partial replacement of "recrystalline" by sphalerite did not materially affect the rock's permeabilitly. In many specimens the disseminated sulphide grains are of the same size as the carbonate they replace, in which case the width and continuity of the intergranular openings are probably unaffected. When the sulphide grains are larger than the grains of the host rock, ore deposition may actually have increased the over-all permeability of the "recrystalline" bed.

ALTERATION OF LIMESTONE AND ATTENDANT PERMEABILITY VARIATION.

Origin of "recrystalline."—Two ideas are prevalent as to the origin of "recrystalline." Newman [87, 88] first advanced the theory that "under pressure the dolomite beds tended to shatter to form breccias in the extreme case, while the limestones tended to flow to form the type of rock known locally under the name "recrystalline." [87] This theory has been restated by Brokaw [89] and by Brokaw and Jones.[90] In the latter publication the authors state: "In contrast to the brecciation of the dolomite, the limestones in the Kingsport which are thin bedded and shaly tend to flow much in the manner of plastic materials when subjected to stress. The highly contorted, discontinuous and abnormally thickened shale zones present are believed to be evidence of flowing and squeezing. In tightly folded beds, the openings formed during deformation have been sealed by flowage of shale and limestone beds."

Currier does not state specifically that he believes limestone flowage con-

[87] Newman, Mark H., Zinc ores of East Tennessee: Eng. and Min. Jour., vol. 139, no. 8, pp. 43–44, 1938.

[88] Newman, Mark H., The Mascot-Jefferson City Zinc District: Internat. Geol. Cong. Guidebook 2, p. 159, 1933.

[89] Brokaw, A. L., Geology and mineralization of the East Tennessee zinc district: Symposium on the geology, paragenesis and reserves of the ores of zinc and lead, 18th Internat. Geol. Cong., p. 64, 1948.

[90] Brokaw, A. L., and Jones, C. L., Structural control of ore bodies in the Jefferson City area, Tennessee: ECON. GEOL., vol. 41, p. 164, 1946.

tributed to the formation of "recrystalline" but he does state, in discussing the origin of tectonic breccias, that "the greater ease of flowage of limestone beds would tend to localize brecciation in the dolomite rather than in limestone."[91] None of these authors has emphasized the widespread occurrence of wavy extinction and the occasional occurrence of warped cleavage planes in "recrystalline" dolomite although these are the most difficult items of evidence to explain by any theory other than "recrystallization" under pressure.

The alterative hypothesis is that the "recrystalline" is the product of alteration of the limestone by magnesium-bearing solutions that circulated through areas of fracturing and brecciation. It is proposed that these solutions were a phase of the ore solution which preceded, was contemporaneous with and also followed the introduction of the sulphides. The best published description of the hypothesis is by Oder and Miller who state:[92]

> We believe that the more coarsely crystalline dolomites resulted from replacement of the limestones by magnesium solutions, which probably circulated along open bedding planes and faulted, fractured, and brecciated areas. Mining has exposed many places in which the "recrystalline" may be followed along the same stratum from the completely altered, well recrystallized and dolomitized rock into totally unaltered fine grained limestone. Such characters as bedding and shaly partings often can be followed from unaltered limestone into medium to coarsely crystalline dolomite.

From this is can be drawn that the authors believe in alteration of the limestone in place without squeezing or other movement which would have disturbed the delicate banding and shaly partings.

Crawford does not state specifically that "recrystalline" is a product of solution action but he indicates indirectly that such is his belief.[93] He is one of the few who believe that not only the coarse dolomite but also the fine dolomite is altered limestone, the two being products of different periods of dolomitization.

In addition to the evidence cited by Oder and Miller, there are several reasons for believing that solution activity rather than flowage was the principal factor in "recrystallization." The "squeeze theory" obviously must call upon solutions for the introduction of magnesium. Simple compression or shearing cannot alter limestone to dolomite. Thus solutions must be present according to either proposal.

In many places near the margin of ore bodies "recrystalline" veinlets can be seen penetrating limestone along obvious cracks in relationships that would be most difficult to explain by a simple pressure theory (Figs. 26, 27A and B).

One of the arguments for "recrystallization" by pressure is the thinning which occasionally is noted in certain "recrystalline" sections within the limits of ore bodies. The Grasselli 10–17 bed, for example, is normally seven feet thick but locally may be only one or two feet thick. Since the top and

[91] Currier, L. W., Structural relations of Appalachian zinc deposits: Econ. Geol., vol. 30, p. 282, 1935.

[92] Oder, C. R. L., and Miller, H. W., Stratigraphy of the Mascot-Jefferson City zinc district: Am. Inst. Min. Met. Eng. Trans., vol. 178, pp. 225–226, 1948.

[93] Crawford, Johnson, Structural and stratigraphic control of zinc deposits in East Tennessee: Econ. Geol., vol. 40, pp. 408–415, 1945.

bottom of this interval are marked by distinctive chert nodules, there is no mistaking the thickness variation. Where the thinning is noted, the rock is invariably "recrystalline." The pressure theory proposes that the missing five or six feet of rock has been squeezed out—presumably resulting in a thicker section in the walls of the altered zone. A significant observation against the pressure hypothesis is that the necessary thickening in the walls of the oreshoots never is noted; the rock in the walls of oreshoots is normal limestone and it shows no evidence of disturbance by the forceful injection of several additional feet of solid material.

It is quite definite from the appearance of the rock that none of what is now limestone has been squeezed. This necessitates the argument that all of the squeezed rock has become "recrystalline." It seems likely that some of the squeezed and presumably recrystallized rock would have escaped dolomitization so that we would expect to find areas of coarse calcium carbonate marble. There are no reports of a coarse-grained rock that was not dolomite ever having been found in the mines.

Most of the "recrystalline" contains grains of several colors—usually various shades of gray predominate. It might be expected, if the rock were squeezed sufficiently to thin layers as much as 75 percent, that color banding and attenuation of grains would be a common occurrence. The reverse is true, for ordinary "recrystalline" is impressively massive. In only one place in the course of several years of almost daily trips into the mines was "recrystalline" seen which was characterized by gneiss-like color banding—obviously due to intense compression. This rock occurs in a very limited area in the 1-South stope at Jarnagin Mine. If the common type of "recrystalline" ever was squeezed and drawn out, all evidence of the fact has subsequently been removed.

The distribution, composition, modes of occurrence, and appearance of "recrystalline" are more readily explained if "recrystalline" is ascribed to solution action. The introduction of the necessary magnesium, the concentration of "recrystallization" near breccia zones that obviously were good channels of circulation, and the penetration of "recrystalline" into limestone along cracks fit logically into the picture of a simple alteration process. The removal of carbonate resulting in the thinning of certain beds within oreshoots can also be attributed to these solutions—probably by an early phase which was not saturated with calcium carbonate. In many recent descriptions of other mining districts, ore solutions are called upon to explain the voids created by removal of carbonate rock.[94] It is believed that the bed thinning in East Tennessee ore bodies will prove to be another example of this type of action. It is significant that the thinning occurs in the midst of zones of concentrated solution circulation.

A great many of the shale concentrations suggested as being due to squeezing are simply the insoluble residues of limestone beds. This is shown

[94] See, for example, Tweto, Ogden, and Lovering, T. S., The Gilman district, Eagle County, *in* Vanderwilt, J. W., and others, Mineral Resources of Colorado, pp. 378–387, 1947. Also, Grogan, R. M., Structures due to volume shrinkage in the bedding-replacement deposits of southern Illinois: Econ. Geol., vol. 44, pp. 606–616, 1949.

by the fact that ½-inch green shale layers pass laterally into limestone with heavy stylolites. A good case can be made that this carbonate removal also is due to the mineralizing solutions.

So far as the wavy extinction of the dolomite is concerned, it is believed that this may result from normal growth of coarse grains through incorpora-

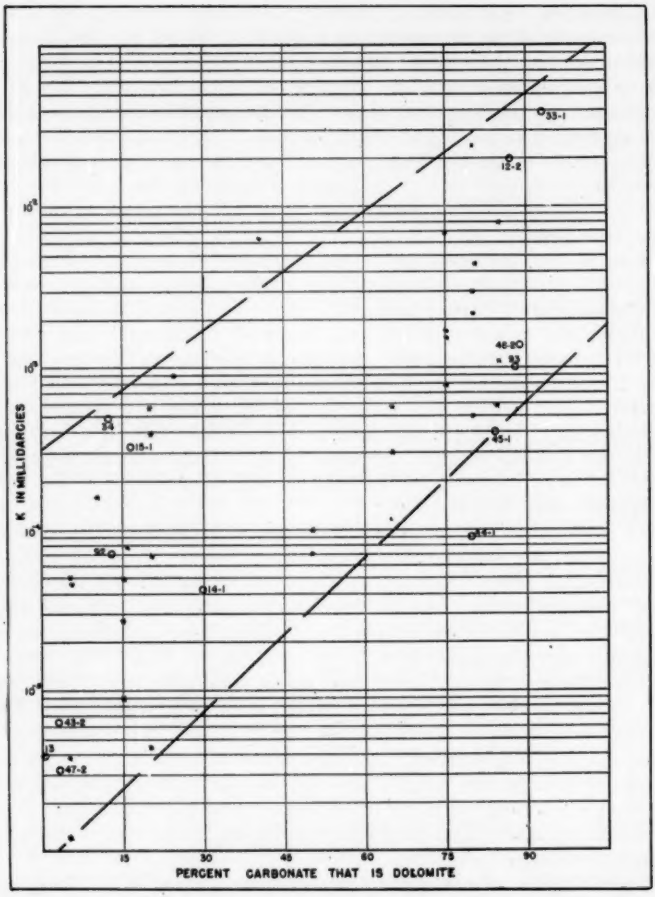

FIG. 28. Progressive increase in permeability with increased degree of dolomitization in rocks from the East Tennessee Zinc District. Replacement of dolomite by jasperoid in 44-1 and 45-1 partially offsets the effect of "recrystallization." Circles indicate specimens actually assayed for magnesium; asterisks indicate specimens with degree of dolomitization estimated.

tion of many randomly oriented smaller grains. Thus the wavy figures need not be "strain shadows." A similar proposal has been made for wavy extinction found in coarse grained quartz in quartz veins.[95] It is significant that the dolomite in the well defined "recrystalline" veinlet crossing limestone in Figure 26 displays good wavy extinction. Wavy cleavage planes possibly could have a similar origin but may truly be due to deformation. They are not so common as wavy extinction.

Effect of "Recrystallization" on Permeability.—As "recrystallization" proceeds, the average grain size increases and also the percentage of the total carbonate that is dolomite. It is easiest to measure the degree of "recrystallization" by the assay for magnesium. Figure 28 shows in graphic form the tremendous change in permeability that accompanies alteration from fine limestone to coarse dolomite. The change is progressive so that at least an ap-

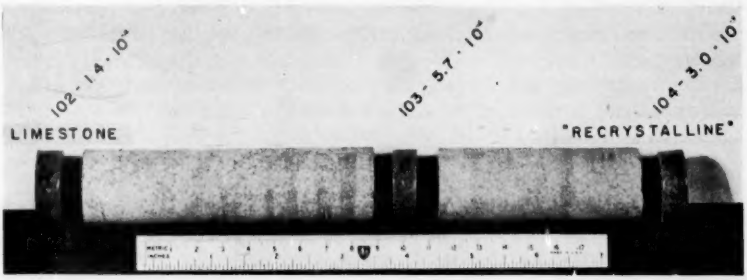

FIG. 29. Section of diamond drill core from S-bed in Jarnagin No. 2 drill hole. On the left the rock is partially altered to "recrystalline"; on the right, there is almost no limestone remaining but the dolomite grains are not extremely coarse. Neither portion contains sphalerite. The permeability of the rock on the right is about 20 times that of the rock on the left—nine inches away. The center disc has a permeability between the values returned by the two end discs. Permeabilities are in millidarcies.

proximation of either the carbonate composition or the permeability can be given if the other is known. Silicification or micro-fracturing may cause misleading results for individual specimens but the trend of the average is unmistakable. Specimen 45–1 contained scattered sphalerite grains in the jasperoid and specimen 12–2 assayed 20.3 percent zinc.

The scarcity of specimens assaying 30 to 75 percent $CaMg(CO_3)_2$ is due to the difficulty in distinguishing rocks of this composition in the hand specimen. A rock 50 percent altered often looks entirely altered. Also, since the complete change takes place over a short distance, the volume of moderately altered rock is small in comparison to the volume of the unaltered or highly altered types. It was thought that the sampling was reasonably continuous across the alteration front but the assays showed otherwise.

[95] McKinstry, H. E., and Ohle, E. L., Ribbon structure in gold-quartz veins: ECON. GEOL., vol. 44, p. 107, 1949.

Figure 29 shows a limestone-"recrystalline" contact intersected by a diamond drill hole. Test discs were cut from three points across the contact zone and they indicate the progressive change in permeability as alteration attacks the original limestone.

It is obvious that, so far as permeability is concerned, the first surge of mineralizing solutions had no reason to choose the limestone layers as avenues of migration laterally from the main open breccia shoots. The figures on pages 881 and 886 show that, if anything, the fine grained dolomites were more permeable than the limestones interbedded with them. Both were very dense. The limestones contained more stylolites but the tests on specimens traversed by stylolites have shown that even when these seams are well defined they are often as tight and impervious as the rock itself.

The limestones, however, did have the inherent ability to change to "recrystalline" and thereby raise their permeability many thousands of times. This had the effect of increasing the size and carrying capacity of the channels of circulation and would be a normal response to the pressure driving the solution.

The permeability of the limestone was so low that diffusion probably contributed largely to the first penetration of the limestone and continued to be important in the "recrystallization" process as the alteration front advanced outward from the main channel. As a block of limestone became "recrystalline," diffusion was still active but its relative importance was less because of the increased capacity for intergranular flow.

Although a lateral component of motion was constantly present as the alteration halo spread ever wider in the favorable beds, the "forward" motion parallel to the main channel must have been of far greater magnitude. The sheath of "recrystalline" would act in every sense as a part of the zone of flow, although of low carrying capacity compared to the open breccia—assuming that the breccia shoot had a free outlet. The forward component constantly replenished the solution along the margin of the channel which was the alteration front. By the time the sulphide phase began, the permeability of the former limestone beds had been so increased over that of the unchanged "original" dolomites that this factor alone was sufficient to account for the virtually exclusive limitation of replacement ore to the "limestone" zones. Disseminated replacement ore is entirely lacking in the fine-grained dolomites—a fact which, on a purely chemical basis, is surprising for they have the same composition as "good recrystalline." The fine dolomites were simply too dense to accommodate important solution flow. If the period of "recrystallization" had followed rather than preceded the sulphides, it is likely that the ore deposits would have consisted almost entirely of open space filling because prior to "recrystallization" none of the rocks would have been sufficiently permeable to permit much intergranular flow outward from the breccia zones.

Alteration in Other Districts.—A marked increase in grain size with or without dolomitization is one of the most common alteration effects wrought by ore solutions passing through limestone. Bisbee, Arizona, Mackay, Idaho, the southeast Missouri lead district, the Tri-state district of Missouri, Kansas and Oklahoma, and Bingham, Utah, are other examples in addition to the

East Tennessee zinc district. Geikie coined [96] the useful term "marmorosis" to identify the process but it is not often found in the literature.

In summarizing his exhaustive study of dolomitization and ore deposition, Hewett says, "With regard to texture, the dolomite resulting from the alteration of limestone is commonly more uniform and more coarsely crystalline." [97] It seems probable that marmorosis exists in many places where no mention of it appears in the literature. If this type of alteration is widespread, the original fine-grained character of the rock may not be known; in extreme cases none of the original rock may remain. In any event an alteration effect that is too general in its distribution is of little use in ore finding and may escape mention.

In many of the districts listed above, whether the ore deposits are of high or low intensity, the marmorosis is described as being guided by fractures and other minor structures. This is particularly evident near the marble-unaltered contact which is usually gradational. Knopf says of Bingham: "Beyond this (the garnet, tremolite, serpentine) zone, the limestones have been changed to either a fine grained rock consisting chiefly of wollastonite and diopside or to a snowy white marble. In this outermost zone fissures, fracture, and bedding planes have facilitated the alterations." [98] His description of the structural control of the alteration would apply to East Tennessee and many other districts. It is probable that structural control was equally effective throughout all the zones of alteration. Due to the completeness of recrystallization or replacement in the more intense zones, the waves advancing from adjoining fractures have met so that the entire rock is altered and the zones of influence of the several channels simply are not apparent.

From the results of the experiments on East Tennessee rocks as well as those on coarse and fine grained limestones and dolomites from Gilman, Colorado, and Hanover, New Mexico, it can be stated with some certainty that marmorosis of any limestone will result in an increase in its permeability and therefore will influence the flow system which prevails later during the circulation of the sulphide-bearing solutions. The ability of the ore solution to penetrate the walls of the fractures is greatly increased. If, in the various mining districts, the rock had been unrecrystallized, it is likely that there would be less replacement ore. A much higher percentage of the sulphides would have been deposited as open-space filling and the total amount deposited would have been less. In a sense, recrystallization has transformed the wall rock into a receptive sponge.

In speaking of ore deposits in limestone, the term "favorable bed" constantly is used to refer to a particular stratum which is mineralized more than its neighbors. Not infrequently such a bed proves to be coarser grained than the average, its grain size being the result of marmorosis of a dense, fine grained "unattractive" limestone. The permeability tests suggest that the favorability of the bed consists of an inherent ability—probably chemical—to

[96] Rice, C. M., Dictionary of geological terms, p. 237, Ann Arbor, 1940.
[97] Hewett, D. F., Dolomitization and ore deposition: ECON. GEOL., vol. 23, p. 848, 1928.
[98] Knopf, Adolph, Pyrometasomatic deposits, *in* Ore deposits of the western United States—Lindgren volume: Am. Inst. Min. Met. Eng., p. 551, 1933.

marmorize upon reaction with early stages of the ore solution while the actual selective deposition of the later sulphides is the result of the physical control of the marmorization on solution circulation.

OTHER GEOLOGICAL APPLICATIONS OF PERMEABILITY DATA.

Method of Ore Transport in the Light of the Permeability Data.—It is so customary to emphasize the relative inefficiency of intergranular flow as compared to flow through open channelways that most people have an inaccurate conception as to the volume of fluid that will pass through solid rock. Once the permeability of a rock type has been measured, it is possible to calculate with reasonable accuracy the quantity of a given fluid which will move through that rock under different combinations of conditions. As an example, assume a channelway 1,000 feet long, traversing a 20-foot bed of "recrystalline" having a permeability of 10^{-2} millidarcies. The calculations to determine the amount of water at 100° Centigrade which will pass through 100 feet of this rock under a pressure differential of 100 atmospheres in 1,000,000 years are as follows:

Solving for Q in the permeability Equation (1):—

$$Q = \frac{KA(P_1 - P_2)}{\mu l},$$

$$Q = \frac{1 \times 10^{-5} \times 18.6 \times 10^{6} \times 100}{.28 \times 3 \times 10^{-3}} \times \text{Time},$$

$Q = 22.1$ cc/sec $= 6.97 \times 10^{14}$ cc/1,000,000 years,

$Q = 768{,}000{,}000$ tons of H_2O which is the amount of water that will pass through the rock under the given conditions.

In this same solid figure there are, at 12 cubic feet to the ton, 167,000 tons of ore which, if it averages three percent zinc, will include 5,000 tons of metallic zinc. This does not seem an insurmountable load even if the solution also is required to bring in 17,000 tons of magnesium and remove an equivalent amount of calcium in the production of dolomite. There is a sufficient volume of flow passing through the rock to account for the ore deposited, even though only a low percentage of the total metal load is dropped within the immediate area.

The calculations are, of course, only approximations. For one thing, the fluid is assumed to be pure water whereas obviously it could not be. However, as modern hydrothermal theory advocates an ore solution of low concentration—Garrels, Dreyer, and Howland, for example, having suggested .1 *N* as a consensus of current opinion [99]—the viscosity used would not be far from correct. The value of the calculation is in showing that in geologic time and under moderate "head" a volume of fluid sufficient for ore deposition can pass through rocks of a type occurring in many mining districts.

[99] Garrels, R. M., Dreyer, R. M., and Howland, A. L., Diffusion of ions through intergranular spaces in water-saturated rocks: Geol. Soc. America Bull., vol. 60, no. 12, p. 1820, 1949.

The desire to have an ore fluid with greater penetrability than an aqueous solution led Brown [100] to discard the hydrothermal theory entirely and call upon metallic vapors "as a medium of far less viscosity and surface tension than water or any other known liquid." [101] The flow equation indicates that viscosity is the major controlling factor governing the volume of a fluid that will pass through a porous medium. Thus, it is worthwhile to investigate just how much is gained in the way of fluidity by abandoning a liquid medium in favor of a gas. Table 6 lists the viscosities of air and water at 20° C, 100° C, and 160° C and of mercury, liquid, and vapor, at slightly higher temperatures. Water, air, and mercury are given because of the abundance of data available and because their viscosity variations are typical of most gases and liquids as indicated in the International Critical Tables.[102]

TABLE 6.

THE VISCOSITIES OF AIR AND WATER AT 20°, 100°, AND 160° C AND OF MERCURY, LIQUID, AND VAPOR AT 250° AND 350° C AND THEIR RATIOS AT THE VARIOUS TEMPERATURES.
(VISCOSITIES IN POISES.)

		Ratio gas/liquid
Air at 20° C	$.018 \times 10^{-}$	1/56
Water at 20° C	1.009×10^{-2}	
Air at 100° C	$.0217 \times 10^{-2}$	1/14
Water at 100° C	$.2838 \times 10^{-2}$	
Air at 160° C	$.0243 \times 10^{-2}$	1/7
Water at 160° C	$.174 \times 10^{-2}$	
Mercury liquid at 250° C	$.96 \times 10^{-2}$	1/19
Mercury vapor at 273° C	$.0494 \times 10^{-2}$	
Mercury liquid at 350° C	$.90 \times 10^{-2}$	1/14
Mercury vapor at 369° C	$.0641 \times 10^{-2}$	

A significant fact at once apparent from Table 6 is that, while the viscosities of the liquids decrease sharply with increased temperature, the viscosities of the gases increase. Thus, at 20° C, air is 56 times more fluid than water, but at 160° C, not far above the suggested temperature of formation of Mississippi Valley type ore deposits, the ratio is only 7 to 1. Data for water above 160° C are lacking but the viscosity of air continues to increase with the temperature and at 500° C is $.0358 \times 10^{-2}$ poises. It is apparent that within the temperature range of ore deposition the viscosity advantage of air over water is reduced to a rather small figure.

The effect of pressure on the viscosity of liquids and gases is not so well known but a few data are available. The viscosity of water at 30° C and 10,000 kg/cm² is $.917 \times 10^{-2}$ poises which is an increase of 15 percent over the viscosity at 30° C and one kg/cm².[103] The viscosity of nitrogen at 25° C

[100] Brown, J. S., Porosity and ore deposition at Edwards and Balmat, New York: Geol. Soc. America Bull., vol. 58, pp. 505–546, 1947. Brown, J. S., Ore genesis, Hopewell Press, Hopewell, N. J., 1948.

[101] Ore genesis, p. 16.

[102] Internat. Critical Tables, vol. 5, pp. 2, 7, and 10, McGraw-Hill Book Co., 1929.

[103] Internat. Critical Tables, vol. 5, p. 11.

as reported by Michels and Gibson [104] is 179.4 micropoises at 10.95 atmospheres and 520.5 micropoises at 454.5 atmospheres. Below 300 atmospheres the viscosity is greater with increased temperature but above 300 atmospheres it decreases as the temperature rises but in neither case is the temperature variation large.

Insufficient data are available for other gases and no data are available on the viscosity of metallic vapors at high pressure. The nitrogen and water data suggest that increased pressure narrows the difference in viscosity between gases and liquids as the liquid viscosity stays fairly constant while the gas viscosity increases considerably.

Garrels, Dreyer, and Howland [105] emphasize the importance of diffusion in the lateral migration of ions from ore fluid channelways. They bring out the fact that the importance of diffusion transport as compared to bulk transport through intergranular openings (i.e., utilizing permeability) increases in rocks with small but numerous intergranular openings. This is due to the greater decrease in bulk transport than in diffusion transport as the intergranular spaces grow smaller. The decrease in diffusion rate is attributed to surface effects and to the fact that a major portion of the diffusion in a saturated rock is through the saturating fluid rather than through the solid grains. Fine grained rocks offer more devious routes through thinner fluid films; hence, diffusion is slower. Despite the apparently similar effect of decreased grain size on the diffusion rate and on intergranular flow, these authors conclude that the rate and distance of diffusive penetration are independent of total porosity or permeability, the quantity which will diffuse being related only to the "effective porosity" on the rock.[106]

Although Garrels, Dreyer and Howland believe that considerable volumes of ions may be transported through many feet of rock at room temperature over periods of time measured in years, it seems unlikely in the East Tennessee situation that diffusion would be comparable in effectiveness to bulk intergranular migration—at least at the time the sphalerite was introduced. The diffusion mechanism was ever present and active and it assumed relative importance whenever the solutions met "tight" rocks. In the actual final emplacement of the sulphides by replacement of carbonate grains, diffusion was surely in control. But, for the major job of transporting the ions through the "recrystalline" from the principal channelways to the final resting place, intergranular flow would be a more efficient method.

One of the more important operations in which diffusion would seem to have been effective was in the advance of the alteration front as previously described. Some of the data of Garrels, Dreyer, and Howland are of interest in this connection. If the conception of an outward-moving alteration front is correct, the flow channels were separated from unaltered limestone by a halo of coarse "recrystalline" which was constantly growing wider. The "recrystalline" would be saturated with ore solution under pressure. It is most likely

[104] Michels, A., and Gibson, R. O., The measurement of the viscosity of gases at high pressures: Roy. Soc. London Proc., series A, vol. 134, pp. 288–307, 1931.

[105] Footnote 99, p. 1827.

[106] Footnote 99, p. 1813.

that a narrow band of the surrounding unaltered limestone would also be saturated, for the permeability tests show that these rocks can be penetrated at moderate pressure. As Garrels, Dreyer, and Howland have shown,[107] this halo of saturation would greatly expedite diffusion and hasten the advance of the alteration front.

Impermeable barriers.—Impermeable barriers which are thought to have impounded or deflected the flow of ore solutions have been described in many districts. In the symposium, "Ore Deposits as Related to Structural Features," 17 such occurrences are cited.[108] In some districts the barrier is a "tight" bed, flow, or sill; in others it is a film of fault gouge or a stylolite. Most commonly the ore lies beneath the impervious material but, if the solutions had a strong lateral component of movement, it may lie on the upper side.

The term "impermeable barrier" carries the idea that an unusually dense rock obstructs flow. Such is often the case but it need not be so. Some of the celebrated examples of the barrier principle consist of a vein system which terminates upward against an unbroken bed. This structural situation is in all likelihood related to rock competency. Whatever the overlying material, it will be less permeable than the open cracks of the vein system and the circumstances for development of a "mushroomed" ore body will be present. The actual permeability of the cap rock need not necessarily be lower than the permeability of the rock traversed by the fissures.

The action of the impermeable barrier in many places is purely diversionary—a stream of fluid obliquely strikes a material through which it cannot readily pass and is deflected. Commonly there results a concentration of flow and consequent increase in the amount of ore deposited alongside the deflecting material. Such occurrences offer no difficulty in explanation.

A more baffling situation is that in which the impervious layer stands athwart the line of flow like an impounding dam. In most examples of this type, the barrier is a flat or nearly flat shale bed or igneous sill or flow while the flow channelway is a near-vertical vein system. The ore mushrooms or pancakes beneath the capping and the vein system extends downward like a root. Lindgren [109] cites certain ore bodies at Rico and Ouray, Colorado, and the siliceous gold ores replacing dolomite in the Black Hills as examples.

Two major problems are presented by this type of occurrence: first, where did the solution go; and second, why did deposition occur below the barrier? Geologists are not in agreement in their replies to either of these queries. Any answer necessitates fundamental assumptions as to the nature of the ore-forming fluid.

The possible answers to the first question are: that the solution went through the barrier; that it went around it, i.e., spread laterally until it found a throughgoing outlet; and third, that the ore solution stopped below the barrier and froze, i.e., it was an ore magma. Omitting discussion of the third

[107] Garrels, R. M., Dreyer, R. M., and Howland, A. L., Diffusion of ions through intergranular spaces in water-saturated rocks: Geol. Soc. America Bull., vol. 60, no. 12, pp. 1809–1828, 1949.

[108] Edited by W. H. Newhouse, Princeton, 1942.

[109] Lindgren, Waldemar, Mineral deposits, 4th edit., p. 200, McGraw-Hill Book Co., New York, 1933.

alternative which has been seriously considered and rejected on other grounds, there remain two choices.

There may be no positive proof that the ore solutions did not spread laterally ad infinitum upon striking the barrier. If the ore is restricted to the immediate vicinity of the diversion point, mining and prospecting probably will not be sufficiently widespread to establish the limits of solution migration, even if they are indicated by some tell-tale rock alteration. But, admitting the lack of definite proof that the solutions did not go around the barrier. there are reasons for believing that at least a substantial part of the fluid went through it. Mackay [110] cites these reasons in an interesting study of the barrier problem. They are: first, that mineral is often found within the barrier itself; second, that other ore bodies are found beneath higher barriers; and third, that "maximum deposition frequently is in places which would be zones of maximum stagnation as far as solutions were concerned if the barriers were truly impermeable." [110] All of these indicate that the barriers are not strictly impermeable but simply less permeable than the surrounding rocks or open spaces through which the fluid had been moving.

Answers to the question: Why did deposition occur below the barrier? are quite diverse and far-reaching in their implications. Newhouse [111] suggests that more fracturing may exist beneath the cover than within it because of a variation in physical properties of the different rock types. Solutions spreading in the permeable shattered layer would encounter a greatly increased rock surface area promoting accelerated chemical reaction as well as faster solution cooling.

Advocates of colloidal ore solutions find support for their thesis in impermeable barrier relations. They suggest that the barrier simply filters out the colloidal particles while the solutions pass on through the semi-permeable capping. Mackay's theory of barrier action [112] is much more elaborate and far-reaching. He proposes that a much larger number of ore deposits owe their origin to impeding action than is generally recognized. Barriers are semi-permeable and their capacity to impede ions, molecules, and particules is based on their effective pore size and the properties of the substance such as ionization and hydrophilic strength. Different barriers, thus, will stop different metals and all the metals have a certain pore size through which they can not pass. Thus, mercury, well known as a "far-traveller," is extracted from a solution only by an extremely fine "filter." If the metal is in true solution, impedance is accomplished by exosmosis. Mackay supports the belief that ore solutions are dilute so that large volumes of water are required.

Some of the conclusions of the present permeability study may contribute to a better understanding of the "impermeable barrier problem." All rocks, except possibly volcanic glasses, can be regarded as permeable in varying degrees. Impermeability is a purely relative term and, compared to an open

[110] Mackay, R. A., Control of impounding structures on ore deposition: ECON. GEOL., vol. 41, pp. 25, 27, 1946.

[111] Newhouse, W. H., Ore deposits as related to structural features, p. 52, Princeton, N. J., 1942.

[112] Footnote 110, pp. 43–46.

channelway, all rocks are impermeable. It is perfectly possible for the ore solution to have gone through the barrier if the driving pressure was maintained.

Newhouse has suggested [113] that, if the solutions spread laterally along the bedding or other surfaces of discontinuity searching out various paths or minor channelways through or around the barrier, deposition of minerals immediately below the barrier might be expected. The permeability investigation suggests that the lateral spreading of the ore solution is important in that it increases the cross-sectional area of the flow channelway at the point where the flow per unit of cross-section is greatly reduced. Thus it tends to compensate for the slower rate of movement by spreading out.

The amount of a given fluid which will penetrate a rock is proportional to the cross-sectional area through which the flow passes. If there is no easier alternative route out of the dead-end channelway described above, the solution *must* move through the rock in considerable volume or become stagnant. As it spreads out below the barrier searching for an outlet, the surface area of the hydraulic system is thereby increased. This increases the capacity for fluid egression by intergranular flow through the walls of the "chamber." Continued lateral expansion may so increase the volume escaping that a balance is struck between the pressure on the system, the volume of fluid available from the source, and the permeability and cross-sectional area of the rocks.

Practically all of the "new" surface area lies on the bottom of the barrier itself. The actual cross-sectional area on the base of the barrier soon far exceeds the cross-sectional area of the feeder channel and, even though the flow-per-unit-area through the barrier is small, the aggregate may be sufficient to allow visible flow through the narrow feeding fractures. Stagnation would thus be prevented. The relatively quiescent state of the fluid where the stream is widest just beneath the barrier may be important in inducing precipitation of the ore minerals.

Meinzer and Wenzel have contributed a thought which is pertinent in a discussion of impermeable barriers.[114] In speaking of ground water aquifers, they say that the lateral movement is much overemphasized while movement perpendicular to the bedding, i.e., through the bounding aquicludes, is underemphasized. The outpourings of artesian wells are overly impressive. Although the beds above and below the aquifer are admittedly much less permeable than the aquifer itself, they may "lose" more water than the aquifer conducts to its main concentrated outlet. This results from the tremendous area of those beds exposed to the hydraulic pressure which more than compensates for their low permeability. This discussion emphasizes the joint importance of area *and* permeability in determining the volume flux. It also indicates the error in Mackay's Figure 8 [115] in which the flow channelway "necks" as it passes through the barriers. It should be shown to be at its widest where it traverses the bed with the lowest permeability.

[113] Footnote 111, p. 52.

[114] Meinzer, O. E., and Wenzel, L. K., Hydrology, Physics of the earth series, vol. 9, p. 450, McGraw-Hill Book Co., New York, 1942.

[115] Footnote 110, p. 41.

The Blind Ore-Shoot Problem.—Blind ore-shoots are interesting because they indicate a more or less abrupt ending of the combination of circumstances which contributed to ore deposition. In the case of blind ore-shoots in veins, it may be simply the concentration of the ore mineral or minerals which ceases or decreases sharply, the main body of the vein structure continuing to the surface or beyond exploration limits. In the case of certain types of replacement deposits in limestone, however, the situation is quite different in that not only all the ore and gangue mineralization but also the attendant alteration effects grow progressively weaker to the point of vanishing. In this latter instance, the outlet of the large volume of solution thought to be necessary for ore formation may be extremely vague.

In his classic discussion of the Mexican manto deposits, Prescott cites,[116] among others, the following principles applying to these ore occurrences:

> 1. The ore bodies are continuous from the point of entrance into the favorable limestones at depth, to the surface, to the point of egress from the favorable beds, or until they become extremely attenuated.
> 2. The area of cross-section of the ore body at any point will not be greater than a small multiple of the area of the normal cross-section nearby, nor smaller than a large fraction of that normal cross-section.
> . . . 5. The ore bodies are essentially chimneys or pipes whether standing vertically and obviously fulfilling the accepted idea of a chimney or pipe, whether inclined at any angle, or even lying horizontally, and, as in pipes, the ore deposited in the portions farthest from the source has passed through and inside the walls of the ore body nearer the source.

Prescott strongly emphasizes the fact that fractures intersecting the ore trend between source and outlet have only minor importance. Principle No. 2, cited above, indicates that the cross-sectional area decreases outward from the source at a fairly constant rate. Prescott states that at Santa Eulalia a typical manto with a "cross section of 400 square meters near its feeding chimney will quite probably have a cross-section of not more than 10 square meters a mile and a half further on."[117]

Most mantos seem finally to break across the beds or to outcrop, thus leaving us in doubt as to the nature of the solution outlet, but a few mantos are known to have abrupt ends.[118] Is it possible that the solutions had no "outlets"? Spurr believed so and advanced these Mexican deposits as examples of ore magmas.[119] Their consideration in the light of this limestone permeability study offers an explanation that may be more acceptable to advocates of the hydrothermal theory.

The fact that the "parent chimneys" are the roots of the ore bodies is indicated by the progressive decrease in size of the mantos laterally away from these chimneys. The location of a manto must be assumed to be the route along which circulation of the ore solution was easiest and in largest volume. In a few places the direction of a manto seems to be related to minor fractures

[116] Prescott, Basil, The underlying principles of the limestone replacement deposits of the Mexican province: Eng. and Min. Jour., vol. 122, p. 247, 1926.

[117] Op. cit., p. 250.

[118] Prescott, Basil, Limestone replacements refute theories of origin: Eng. and Min. Jour., vol. 147, no. 4, p. 88, 1946.

[119] Spurr, J. E., The ore magmas, vol. 2, pp. 875–876, McGraw-Hill, New York, 1922.

but in most places there is no apparent structural control and the guiding influence on circulation must have been some rock property—quite probably permeability. Much of the solution migration thus was through the rocks themselves, and the ore solutions by depositing ore and gangue minerals have marked the routes of easiest circulation.

Solution migration along these relatively permeable avenues must have been slow in comparison to flow in an open crack but the aggregate volume need not therefore have been small. So long as new fluid was introduced from the source at sufficient pressure to overcome the rock's resistance to flow lateral migration would continue. In most cases, the solution "front" would intersect a fracture or a chimney which served as an outlet and flow would continue so long as there was driving pressure from the solution source—the volume of flow varying directly with the pressure differential.

Prescott has stated that the mantos acted as pipes or tubes directing circulation and that the ore deposited in the farthest reaches passed through the parts of the pipe nearer the source. The fact that these pipes decrease in cross-section laterally away from the source presents a serious problem to an understanding of the plumbing system of the hydrothermal solution—especially since the far end of the manto may be a complete "dead end." Assuming for the minute that the manto in question does not really end but just has a small outlet, the volume of circulation in the entire system would be controlled by the small outlet and the rate of solution flow in the wider parts of the manto would be progressively slower as the cross-sectional area increased. Following Prescott's reasoning, if the manto does have a definite "dead end," there could be no "circulation" and one is forced to fall back on some injection hypothesis of ore genesis. Prescott is inclined to such an explanation although he refrains from using the word "injection." [120]

Although the rock along the route chosen by the ore solution was obviously more permeable than the adjoining rock in the channel walls, nonetheless the wall rock had a definite permeability and would have to transmit a volume of ore fluid in accord with this ability. At the time the ore solution was present, the entire "plumbing system" was under pressure and the lateral leakage through the walls of the main pipe would everywhere be proportional to the permeability of the walls and inversely proportional to the distance to an adjoining escape channelway. The prevailing pressure would depend on the generating capacity at the solution source and on the rock resistance to flow. The pressure in this type of circulatory system would exceed certainly that which would obtain at comparable depth in an open channelway with a free outlet because of the tremendously greater frictional resistance to flow.

It seems probable that the extent of the manto would relate to the volume-producing capacity of the ore fluid source, for the volume of leakage through the manto walls would be forced to adjust to equal the production. If the production volume increased, the discharge might be increased through length-

[120] In personal communication to J. E. Spurr reported in Spurr, J. E., Lead-zinc chimneys in limestone: Eng. and Min. Jour., vol. 122, p. 297, 1926. See also Prescott, Basil, Limestone replacements refute theories of origin: Eng. and Min. Jour., vol. 147, no. 4, p. 88, 1946.

ening of the manto or by increased leakage resulting from a rise in pressure. Probably both would occur until a balance was restored.

In the system described, the actual volume of fluid moving through the end "outlet" of the manto would be much less than the original volume entering the manto because much of the fluid would have escaped through the channel walls. The amount of flow emergent per unit of cross-sectional area at the end, however, would be many times that of any other point. The flow through the walls at any one point would be insignificant and insufficient to accomplish notable sulphide deposition. The progressive decrease in size of the manto (the flow channel) would in part reflect the cumulative loss through wall leakage.

If, in the growth of a manto laterally from its parent chimney, a balance were met between the rate of solution production and wall leakage before an "outlet" was intersected, a "blind manto" would result. Further flow might increase the grade of the deposit but it would not increase its volume. A similar situation might result from the "dead ending" of the main permeable channelway due to an "accident" of sedimentation. Recognition of the finite permeability though relative impermeability of the manto walls leads to the conclusion that an ore magma is not necessarily indicated by such occurrences. The tremendous area of the walls of the flow channel permits leakage that is great in the aggregate. A concentrated ore solution is not required to account for the ore deposited.

Deposition of the metal ions by an ore solution passing from pervious to less pervious rock does not need to be a question of "straining" although that mechanism would suggest itself at once to advocates of colloidal transfer. It is believed that deposition may just as readily be the result of solution neutralization or some other chemical reaction with the wall rock or of some physical effect such as change in the rate of solution flow, the rate of heat loss, or a crystal surface effect. It is suggested that the solution is dilute and that the reaction resulting in sulphide deposition occurs quickly when the solution comes in contact with fresh wall rock. The solution is thereupon rendered inert and passes on out of the system without effecting the rest of the rock with which it comes in contact. The wall rock, once altered or replaced by ore, is in turn rendered inert to more of the same solution so that the next volume of solution must travel farther along the most permeable route before depositing its load. Thus a manto "grows."

Several lines of evidence indicate that solutions may move through limestone (and other rocks as well) without causing any reaction and without leaving any direct evidence in the limestone that flow occurred. From chemical reasoning, it seems perfectly logical that an inert fluid can pass through rock open spaces and leave no trace. In the permeability tests, air and other gases were passed through rocks which showed no visible after effects of the flow. Probably there were no effects. Several natural occurrences are noted below in which similar non-reactive flow seems to be indicated by indirect evidence. It seems reasonable to believe that much more flow through rock pores has occurred than can be proved.

R. H. Griffin has produced an interesting study of the dolomitization of the lower Platteville limestone near Minneapolis, Minnesota.[121] By sawing and staining hand specimens he determined that the dolomite is distributed through the limestone in an "anastomosing, irregularly pipe-like manner." [122]

Griffin's description of the dolomite areas bears repetition:

> Megascopically, dolomite patches are extremely irregular in shape and variable in size. Some, up to 7 cm in length, are elongate parallel to the bedding, but this is not universal. Indeed others are nearly at right angles. Many are connected by thin stringers and quite commonly irregular patches lie in zones parallel to the bedding, along shaly partings or as tongue-like extensions from these. A three-dimensional model . . . shows that large areas of dolomite form solid structures of very irregular shape extending laterally and vertically through the rock. Few patches are truly isolated and these usually are of small size.[123]

All primary rock features are altered. As there is no control by jointing, the joints are assumed to be post-dolomitization. Griffin concludes that, while shale partings were the principal flow guide, the migration of the dolomitizing solutions through the rock away from the partings was controlled by permeable zones in the limestone.

A significant item in the preceding description is the reference to "tongue-like extensions." The Mexican mantos might also be regarded as "tongue-like extensions"—of the parent chimney. The dolomite extensions apparently may be merely narrow necks joining larger areas or they may be true "dead ends." The dolomitization is ascribed to circulation of magnesium-bearing solutions but it is apparent that circulation in these dead-end protrusions would be impossible—unless it be conceded that once a given volume of solution has expended its dolomitizing power, it can pass on through the surrounding limestone without affecting it. It is believed that that is what happened. There is a great difference in scale between these dolomitized structures and the great mantos but the problems of fluid circulation are much alike.

In the southeast Missouri lead district, the type of wall-rock alteration known as "fingering" offers an unusual opportunity for study of the flow of solutions through rocks for the flow channels are stained and well defined. Tarr describes this remarkable structure in some detail.[124] It is aptly named "finger rock." [125]

There is much yet to be learned about the size, shape, and distribution of "fingers" but the following notes give a generalized picture of this unusual alteration.

In the vicinity of mineralization, the normally tan or gray-spotted rock in a 120-135-foot zone in the lower part of the Bonneterre dolomite formation is altered to a reddish brown or red color. Chemically the process seems to involve oxidation of ferrous iron to ferric iron. Where the alteration has

[121] Griffin, R. H., Dolomitic mottling in the Platteville limestone: Jour. Sedimentary Petrology, vol. 12, pp. 67–76, 1942.

[122] Idem, abstract.

[123] Idem, pp. 70–71.

[124] Tarr, W. A., Origin of the southeastern Missouri lead deposits: Econ. Geol., vol. 31, pp. 719–721, 1936.

[125] A term originally proposed by R. E. Wagner.

gone to completion, entire beds two to three feet thick may be changed in color. Where the process is incomplete, reddish, irregular, finger-like or icicle-like structures extend outward into the rock from the bedding planes. They vary from less than an inch to several inches in diameter and from a few inches to a foot or more in length. Usually they taper slightly either upward or downward. The beds are almost horizontal and the "fingers" are practically vertical. Most "fingers" extend entirely through a given dolomite layer from bedding plane to bedding plane but some end in the middle of a bed. A wavy, dark, shaly seam bounds most "fingers" and sharply defines them. In cross-section, as seen in a stope back, the "fingers" appear as concentric bands of various shades of red or gray suggesting a cone-in-cone structure. Tarr noted a resemblance to stylolites in the gross "finger" pattern as seen on a stope wall and also in the bounding wavy shale seam. "Fingers" may be so abundant that they touch each other or they may be separated by considerable widths of unaltered, tan or gray-spotted rock. Certain beds in the 120-135-foot zone alter more easily than others and many layers are devoid of "fingering" except in areas of unusually intense alteration.

Both the "fingers" and the surrounding rock are dolomite and chemical analysis reveals little difference in their composition except that more of the iron is in the ferric state in the reddish portions. Finely divided marcasite or pyrite can be readily detected in the unaltered rock; it is less abundant or absent in "fingers." The texture of the dolomite in the "fingers" is not noticeably coarser than the enclosing rock; some "fingers" seem to be finer grained than their surroundings. Most "fingered" layers are mottled mixtures of extremely fine to coarse dolomite.

"Fingers" represent the pathways of fluid movement. Because of the staining we are able to detect them. It is most unlikely that one pore-volume of fluid would have had a strong enough oxidizing nature to remove the iron sulphide in the flow channel. More probably, it was a long-term process. In a few stopes, "hollow fingers" have been found in which the dolomite within the flow channel has been dissolved by the circulating ore fluid. This too would necessitate long-continued solution action.

No one has advanced an entirely satisfactory explanation of the shapes of "fingers." In form some of them resemble chimneys of ore in other districts which have been ascribed to the concentration of solution circulation at the intersection of fractures—but "fingers" show no relation to visible cracks. Ascribing the structure to an original distribution of permeability in the rock does not completely satisfy because there is evidence that these rocks are limestones that have been dolomitized as part of the ore-forming process; yet we do not find dolomite "fingers" traversing limestone as would be expected. Nonetheless it seems indubitable that the distribution of permeability controlled the distribution of "fingers," whatever the origin of the permeability pattern may be.

As in the case of the dead-ending mantos in Mexico and the "tongue-like extensions" in the Platteville limestone, the dead-ending "fingers" in the Bonneterre pose a problem in fluid circulation unless it be admitted that solutions can move through rocks without affecting them. The reddish alteration

process in southeast Missouri is visualized as follows: slightly oxidizing altering solutions entered the formation along major fractures and spread laterally along various types of controlling structures. Bedding planes were utilized as secondary avenues of flow. From these bedding planes the fluid passed outward into the overlying and underlying rocks along paths of greatest permeability. In certain rocks it encountered reducing conditions in the form of iron sulphide widely disseminated in tiny grains. Each volume of solution oxidized the sulphide to the extent of its ability and then passed on through the rock without further affecting it. By gradual extension, the "fingers" reached through the entire thickness of the rock layer. Further solution flow then resulted only in increased "finger" diameter. If the flow was in sufficient volume, "fingers" grew until they coalesced so that the whole bed was altered. The concentric banding of the reddish coloration may indicate that the solution moved in surges. Later sulphide-bearing solutions in general followed the same paths of circulation so that the general vicinity of altered rock is a favored locus for galena.

The purpose of this somewhat extended discussion of "blind" ore shoots or "blind alteration shoots" is to stress the fact that no flow outlet in the sense of a well defined aperture is necessary to the hydrothermal theory of ore deposition. Measurement of the permeabilities of limestones and dolomites from a number of different mining camps impresses the fact that no carbonate rock is truly impermeable. All of them have a finite ability to transmit fluid which, over a long time under reasonable pressure, may be in considerable volume. This ability is always present and whenever a carbonate rock lines an opening containing fluid under pressure, there *must* be leakage in proportion to the rock permeability, the fluid viscosity, the differential pressure, and the thickness of rock to the nearest flow outlet. As the surface area of the solution-filled opening is always many times greater than the cross-sectional area perpendicular to the main direction of movement, the leakage may be great enough to allow the replenishment of the ore solution in the opening and consequent significant sulphide deposition. If the solution reacts with the limestone until an equilibrium is reached, it is possible for fluid movement to continue without leaving any visible evidence of the flow. Prescott's failure to find "evidence that anything had passed—gas, liquid, or solid" does not compel acceptance of his conclusion that "apparently there were no volatiles, with or without metal load, left over when deposition was completed and consolidation took place." [126]

Ore Deposition from "Quiescent" Solution.—Evidence suggests that at the time when much of the sphalerite in the brecciated shoots in East Tennessee was deposited, the ore solution was practically quiescent. The evidence leading to this conclusion is the widespread occurrence of the open-space-filling type of sphalerite in a preferential location on top of the breccia fragments. This distribution has been noted by other observers [127] and it is

[126] Prescott, Basil, Limestone replacements refute theories of origin: Eng. and Min. Jour., vol. 147, no. 4, p. 89, 1946.

[127] Behre, C. H., Jr., *in* discussion at the Southeast Minerals Conference, Knoxville, March, 1949. Also Oder, Charles R. L., and Hook, John W., op. cit., p. 75. See also Figure 19.

general enough to make it possible to orient the top and bottom of a large percentage of randomly selected pieces of breccia ore.

The sphalerite appears to have been precipitated from solution under gravity control and to have settled to the horizontal or subhorizontal upper sides of the fragments. Generally the "accumulated" layer or crust is 1/8-inch to 1/2-thick and the sphalerite drapes over the edges of many fragments like wet snow overhanging the eaves of a building. If one were to follow Newhouse and Stoiber's method [128] of determining the direction of solution flow, the conclusion would have to be that the movement was vertically downward. This is unlikely because the footwall beds of the ore bodies often are unbroken and, hence, it is doubtful whether there are flow outlets in that direction. The suggested origin by precipitation from a quiescent solution under gravity control appears more likely. Bastin found a similar localization of late minerals on top of earlier crystals in the southern Illinois fluorspar district and likewise concluded that deposition was under gravity control.[129]

Although the ore solution appears to have been quiescent at the time of sulphide deposition, it does not follow that it was stagnant. Quiescence may have existed during periods between flow in a pulsating flow system which many times replenished the supply of metal ions. Or, solution flow may have been constant but simply so slow that precipitation occurred as if from a perfectly still liquid. The cross-sectional area of the interfragment open spaces in the breccia shoots of the East Tennessee district was in all probability many times that of the feeder channelways. Hence, while the flow through the relatively restricted feeder fractures may well have been readily apparent, the much dispersed flow through the breccia could have been imperceptible. Flow through the ultimate outlet could have again been concentrated and relatively rapid. In such a system, constant replenishment of the solution in the breccia mass would prevent stagnation but crystal precipitation would be under gravity control because the motion through the breccia was so slow. Whatever circumstances resulted in quiescence or near-quiescence, it is evident that the solution which deposited much of the sphalerite in the Mascot-Jefferson City area was not "whistling through" the open ground.

If a certain volume of solution is required to provide the necessary ions to make an ore deposit, it follows, of course, that a slow moving solution must move for a longer time to "accomplish the objective." During all of the flow period, the walls of the flow system must be under pressure from the ore solution. If the volume rate of flow is relatively slow, the proportion of solution "loss" through intergranular flow through the walls will be high compared to those flow systems in which there is rapid movement through a well defined channelway, assuming, of course, that the total flow volumes are the same. Thus it may hold that some ore deposits occurring in open spaces which show no evidence of strong directional flow owe their existence in substantial part

[128] Newhouse, W. H., The direction of flow of mineralizing solutions: Econ. Geol., vol. 36, pp. 612–629, 1941. Stoiber, R. E., Movement of mineralizing solutions in the Picher field, Oklahoma-Kansas: Econ. Geol., vol. 41, pp. 800–812, 1946.

[129] Bastin, E. S., The fluorspar deposits of Hardin and Pope Counties, Illinois: Illinois Geol. Survey Bull. 58, p. 39, 1931.

to flow resulting from "leakage" utilizing the intergranular permeability of the wall rock.

SUMMARY AND CONCLUSIONS.

The status of our knowledge of rock permeability has been reviewed in the light of fundamental work done since Rove's pioneer study and an attempt has been made to evaluate the influence of permeability on ore deposition in limestones and dolomites. Over 1,000 permeability tests were made, principally on rocks from the East Tennessee zinc district. These tests were made in a permeameter especially designed to test rocks with permeabilities in the range 10^{-2} to 10^{-7} millidarcies. This apparatus greatly increases the rate of permeability measurement and permits the use of different gases and liquids interchangeably.

Since the general practice in determining how much of a given liquid a rock will transmit is to measure the rock's permeability by passing a gas through it and then apply a viscosity correction, an investigation has been made of the relative merits and accuracies of gas and liquid flow tests for permeability determination. Klinkenberg has shown that only at infinite pressure do gas results check liquid results. At lower pressures gas tests give high values due to a slip effect. Percentagewise, the "error" is greatest in dense rocks such as the limestones and dolomites involved in the present study. Other potentially important sources of error in using gas test results to determine capacity for liquid transmission are clay swelling and adsorption. Of less importance are ionic concentration, streaming potential, temperature variation, surface tension, and electrical conductivity. In new areas it is necessary to run some liquid tests as well as gas tests to determine whether any of these errors are serious. In East Tennessee rocks, none were significant and the gas and liquid tests gave comparable results although the "liquid permeability" was always less than the "gas permeability."

The East Tennessee zinc district lends itself particularly well to studies of the relationships between rock properties and ore distribution because the stratigraphy and the stratigraphic distribution of the ore are well known. The permeability values fall into three main groups, corresponding to the three main rock types: fine grained "original" dolomite, dense, fine grained limestone, and coarse dolomitic marble (locally known as "recrystalline") which is an alteration product of the limestone in the vicinity of mineralization. The average K values of the three groups are: 8.1×10^{-5} millidarcies, 2.7×10^{-5} millidarcies, and 5.9×10^{-3} millidarcies, respectively. As all of the specimens were collected in the vicinity of the mining areas, there were probably no specimens of completely unaltered limestone. All of the rocks assayed showed some magnesia. The least altered specimen of those which were analysed returned a permeability of 6×10^{-7} millidarcies.

Although the limestone has a somewhat lower permeability than the "original" dolomite with which it is interbedded, disseminated replacement ore is practically limited to altered limestone. This limitation is particularly striking because the compositions of the "original" dolomite and the altered limestone are virtually the same. As there is a tremendous difference in the capacity of these two rock types to transmit fluids, it is suggested that the freer

circulation of the solution through the "recrystalline" is responsible for the concentration of disseminated replacement ore in that rock type.

Although the limestone is less permeable on the average than the "original" dolomite, it has the distinct advantage of being able to "recrystallize" and thus greatly increase its permeability. Since the favorable beds in many mining districts in which the ore occurs in carbonate rocks are coarser than the unfavorable beds, permeability is a likely factor in the selective localization of the ore. In many of the districts, rock alteration prior to sulphide introduction has effected a coarsening of grain in the favorable beds so that at the critical time of metal introduction certain layers permitted a much greater volume of circulation than others. The inherent ability of certain layers to recrystallize is probably a major factor in determining which beds will be favored by ore deposition.

Permeability tests on carbonate rocks from several mining districts and on a few igneous rocks lead to the conclusion that probably no rocks, except possibly volcanic glasses, are truly impermeable. All of the rocks tested showed a finite ability to transmit fluid. Over geologic time and under reasonable pressure, the flow will be in considerable volume. Through rocks as permeable as East Tennessee "recrystalline" the flow may be far in excess of that necessary to transport the ions necessary to form an ore deposit. A rough calculation which is presented of the volume of water which would be forced through rock of the "recrystalline" type under hypothetical but not unreasonable conditions confirms this fact.

This capacity of wall rocks to permit flow is always present and, whenever a rock bounds an opening containing fluid under pressure, there *must* be "leakage" in proportion to the rock permeability, the fluid viscosity, the differential pressure, and the thickness of the rock to the nearest flow outlet. Recognition of this fact offers a possible explanation of such problems in ore deposition as "blind" ore shoots in manto deposits and deposits below "impermeable barriers." It does not seem necessary to call upon an "ore magma" or a highly concentrated ore solution. In most ore-solution conduits the surface area of the conduit far exceeds the cross-sectional area. Although the rate of flow per unit area is faster through the opening than through the walls, the total volume of solution "lost" through the walls will be considerable and quite possibly in many cases is in sufficient volume alone to account for the mineral deposited in the conduit.

Likewise there seems to be no need to call upon an ore fluid with greater penetrability than an aqueous ore solution. The viscosities of most gases increase with increased temperature, while those of most liquids decrease. Hence, gases have much less advantage in fluidity over liquids at a few hundred degrees Centigrade than at normal room temperature.

This permeability study indicates that in all probability a sufficient volume of dilute ore solution could pass through carbonate rocks to account for all the ore deposits found in them.

St. Joseph Lead Co.,
Bonne Terre, Missouri,
March 21, 1951.

GEOLOGIC STUDIES IN A NEW MEXICO POTASH MINE.[1]

JOHN C. DUNLAP.

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ABSTRACT.

More than 80 percent of the potassium salts produced in the United States comes from three mines in Eddy County in southeastern New Mexico, where these salts occur in gently dipping beds of the upper Permian Salado formation. Sylvite (KCl) is produced from the same stratigraphic level at each of the three mines, and langbeinite ($K_2SO_4 \cdot 2MgSO_4$) from a level 100 feet higher at one of the mines. Detailed geologic studies of the langbeinite zone have shown that the potash salts are discontinuous within the zone and occur as irregular-shaped lenses. These studies further show that the potassium salts are concentrated where certain stratigraphic marker beds are farthest apart and are absent or occur only in trace quantities where the marker beds are close together. Variation of the distance between marker beds results from the relative change in position of the lower bed; this change is interpreted as resulting from irregularities on the floor of the evaporating pan that existed at this stage of salt deposition. Areas in which the most prominent marker bed is locally structurally low, and which contain the concentrations of potassium minerals, are thought to represent basins, whereas areas in which this bed is locally structurally high represents ridges.

Langbeinite and sylvite occur in the same stratigraphic interval; the lateral transition from a concentration of one mineral to the other and from a concentration of one of the potassium minerals to halite is often abrupt and the interface is not marked by any recognizable stratigraphic or structural feature. Langbeinite generally predominates where the distance between marker beds is maximum, and sylvite is more abundant where the distance is somewhat less than maximum.

[1] Publication authorized by the Director, U. S. Geological Survey.

The interpretation made is that the potash salts were precipitated directly from brines in small open basins at the top of the accumulating salt body and were subsequently covered by succeeding layers of salt, or that they were precipitated after burial from potash-rich brines that were trapped in porous but impermeable halite in the basins. The first possibility is favored because of the writer's belief that variations of temperature were very important and were greater in the open basins. The lateral change from langbeinite to sylvite or to halite at the same stratigraphic level may have been influenced by irregularities on the floor of the evaporating pan that resulted in segregation of brines of different richness, and caused variation in temperature of the brines; factors that would result in the precipitation of one salt rather than another.

The writer believes that continuation of the type of study described in this report offers the only hope of finding a geologic guide to the distribution of the potash ore bodies.

INTRODUCTION.

More than 80 percent of the production of potassium salts in the United States comes from three mines in Eddy County in southeastern New Mexico, about 20 miles northeast of the town of Carlsbad. One mine was opened by the United States Potash Company in 1931, another by the Potash Company of America in 1934, and a third by the International Minerals and Chemical Corporation in 1940.

The name, composition, and K_2O equivalent of the most abundant potassium salts in the New Mexico deposits are as follows:

Name	Composition	K_2O equivalent (percent)
Carnallite	$KCl \cdot MgCl_2 \cdot 6H_2O$	17.0
Langbeinite	$K_2SO_4 \cdot 2MgSO_4$	22.7
Polyhalite	$K_2SO_4 \cdot MgSO_4 \cdot 2CaSO_4 \cdot 2H_2O$	15.6
Sylvite	KCl	63.2

These minerals occur in several beds in the upper Permian Salado formation, which consists almost entirely of halite and minor anhydrite. Sylvite is produced from the same stratigraphic level at each of the three mines and, in addition, langbeinite is extracted from a zone 100 feet stratigraphically higher in the mine of the International Minerals and Chemical Corporation. Neither carnallite nor polyhalite had been mined to 1947. During 1946 daily production from the three mines totaled about 12,000 tons of crude salts.

In order to gain an understanding of the geologic and paleogeographic conditions that were instrumental in localizing the accumulations of soluble potassium salts, knowledge of which should prove useful in prospecting for additional reserves, the U. S. Geological Survey started detailed geologic studies in the mine of the International Minerals and Chemical Corporation in November 1945. The information concerning stratigraphic and mineral relationships presented in this paper is the first result of this continuing study; the statements are principally descriptive, because any explanation of genesis and distribution of the various potassium salts involves complex geochemical reactions that are not fully understood at present. This paper is presented with the hope of stimulating thought and discussion of the described relations.

ACKNOWLEDGMENTS

The writer wishes to express appreciation to the International Minerals and Chemical Corporation for extending an invitation to the U. S. Geological Survey to make a geologic study of its mine. Mr. G. T. Harley, general manager, Mr. G. E. Atwood, chief metallurgist, Mr. G. C. Weaver, chief engineer, Mr. Charles Hicks, geologist, Mr. W. P. Morris, mine superintendent, and all other members of the staff with whom the writer came in contact during the investigation were most helpful and cooperative. Especial thanks are due Mr. Jerry Tong, foreman of the 800 level, the level with which this paper deals. Mr. Tong's habit of close observation enabled him to call attention to many interesting features of the deposits. Thanks are due also to Mr. Chao Chia-Hsiang, geologist of the Mineral Exploration Bureau of China, who assisted in a most able manner in mapping that part of the 800 level shown in the illustrations. The writer is grateful to Mr. Eugene Callaghan, formerly of the U. S. Geological Survey, who made preliminary plans for the mine mapping, obtained permission to work in the mine, and assisted in starting the work. During the course of the studies much help was received from Mr. R. H. Allport, representative of the Mining Branch of the Conservation Division of the U. S. Geological Survey, who provided office space and records and made helpful suggestions.

REGIONAL GEOLOGIC SETTING.

The complex character, distribution, and structure of the Permian rocks in southeastern New Mexico and west Texas have been described by many authors (1, 2, 3, 4).[2]

The relatively more depressed areas termed "basins" received a type of sediment different from that of the higher "shelf areas." Lime-secreting organisms flourished at times around the edges of the basins, and their activity resulted in the accumulation of thick reef limestones. Evaporites were laid down at various times, both on the shelf areas and in the basins, and constitute an important part of the Permian rocks. During late Permian time evaporite deposition was predominant and the Ochoa series was laid down, at first only in the Delaware basin, a depressed area in the western part of the larger Permian basin, but later this series extended far onto the shelf areas.

The Ochoa series has been described in considerable detail by Adams (1); only a brief description is given here. In ascending order the series has been divided into the Castile, the Salado, the Rustler, and the Dewey Lake formations. The Castile does not extend outside the Capitan reef that encircles the Delaware basin, therefore is found only in that basin. It consists principally of laminated anhydrite and calcite, but in the northeastern part of the basin contains considerable halite. Adams (1) states that the average thickness is between 1,500 and 1,850 feet and the maximum thickness is more than 2,100 feet.

The Salado formation, which contains the commercial deposits of potassium salts, consists principally of halite, but contains numerous beds of anhy-

[2] Numbers in parentheses refer to Bibliography at end of paper.

drite, polyhalite, silt, and clay. Toward the southwest end of the Delaware basin it contains much anhydrite, and at the southern end of that basin is believed to grade into dolomitic limestone. The Salado is not restricted to the Delaware basin but extends far onto the shelf area to the east and northeast. To the west it is missing, owing either to nondeposition or to erosion. Adams (1) gives the maximum thickness of the Salado as more than 2,200 feet in the northeastern part of the basin.

The Rustler formation consists principally of evaporites but contains dolomite, sandstone, silt, and shale. The formation shows a nearly complete sequence of evaporites when traced from the southwest to the northeast portions of the Delaware basin (1). In central Eddy County, a section measured by Lang (5) is 515 feet thick.

The Dewey Lake redbeds are slightly less than 350 feet thick (1).

STRUCTURAL AND STRATIGRAPHIC POSITION OF THE POTASH DEPOSITS.

The three potash deposits are at the north border of the Delaware basin. The deposit worked by the Potash Company of America is on the margin of the shelf area, just north of the buried Capitan reef; the deposit worked by the United States Potash Company in part overlies the reef; and the deposit farthest southeast, that worked by the International Minerals and Chemical Corporation, is in the Delaware basin, south of the reef.

In the vicinity of the International mine the Salado formation has a maximum thickness of about 1,400 feet. It thins rapidly to the west because of truncation, and has a very irregular surface as a result of solution by ground water. Numerous core-test holes have disclosed persistent beds of polyhalite-anhydrite, which can be correlated in the area near the three mines. The most prominent bed averages slightly more than 8 feet in thickness in the vicinity of the International mine, is dominantly white or light-gray fine-grained anhydrite, and occurs about 70 feet stratigraphically above the sylvite zone that is mined.

At the International mine the soluble potassium salts are concentrated in four zones in the Salado formation and consist chiefly of sylvite, langbeinite, and carnallite. The upper zone is 250 feet [3] below the eroded top of the Salado and contains a mixture of sylvite and carnallite; it is not mined at present. The next, the 800 level, is 100 feet lower; it contains langbeinite and sylvite, and is the only deposit of langbeinite in the world that is being mined. About 65 feet below the 800 level is a zone containing a mixture of langbeinite and sylvite that is not being mined. The 900 level is mined for sylvite but contains very small proportions of langbeinite and other potassium sulfates.

DESCRIPTION OF 800 LEVEL.

The workings on the 800 level are irregular as a result of the erratic distribution of bodies of langbeinite, the principal potash mineral mined. In

[3] The four zones of soluble potassium salts are referred to as the "700 level," the "800 level," the "850 level," and the "900 level," these names being based on the approximate depths below the collar of the shaft. Actually, the floors of the levels are, respectively, 687, 787, 856, and 902 feet below the ground surface.

June 1947 the workings covered an area of approximately 0.55 square mile and exposed a vertical section that averaged slightly more than 7 feet in height. The floor of the workings is smooth and is nearly horizontal as it conforms to the regional dip. The room-and-pillar method of mining is used, and the walls of the double entries that serve as main haulageways give an excellent, nearly continuous exposure of the marker beds and the various saline minerals. The mine is entirely dry except for a very small seepage of residual brine that appears on some newly exposed faces.

GEOLOGY OF 800 LEVEL.

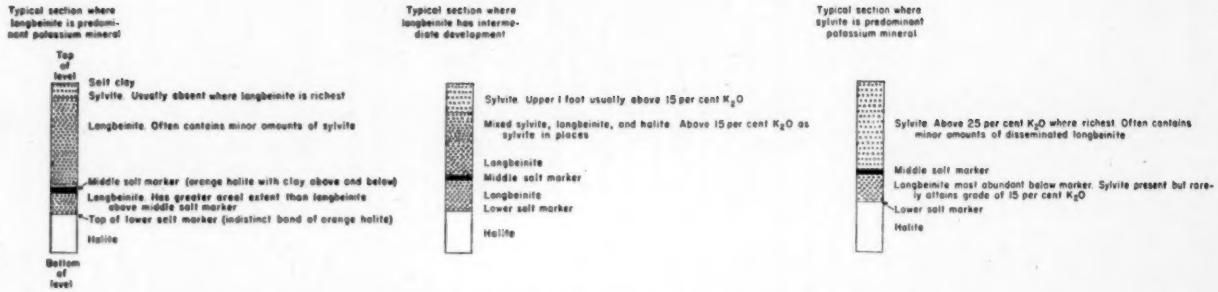
Stratigraphy.—Two persistent stratigraphic marker beds in the Salado formation are exposed on the 800 level and are indispensable in studying the geology of the level. The upper marker is a bed of salt clay that ranges from a fraction of an inch to about 0.5 foot in thickness. It is green or reddish-brown; the color is due to green or reddish-brown clay that constitutes about 30 percent of the bed. This clay forms a plane of weakness in the salts, and provides a smooth roof for the mining operations because it generally is present at the top of the concentrations of potassium minerals.

The middle marker is a bed of orange halite that ranges from 0.1 to 0.6 foot in thickness, and is accentuated by a concentration of clay above and below. This bed has long been used as a vertical control in development and is known as the middle salt marker. Microscopic examination has shown that the orange color is due to minute crystals and blebs of orange polyhalite. This bed is generally about 4 feet above the floor and persists through the langbeinite bodies. In langbeinite-rich areas it may be composed principally of langbeinite and the color may be subdued, but generally it is still recognizable, though at places it cannot be identified for a few feet or tens of feet.

A third marker bed can be identified at many places on the 800 level but is not nearly so distinct as the two beds described above. Like the second bed described, it is composed of orange halite, but lacks the associated concentrations of clay that help to identify the middle salt marker. It is known as the lower salt marker. The relative positions of the three described beds are shown on the columnar sections, Figure 1.

Structure.—The beds of the Salado formation exposed on the 800 level are nearly horizontal, dipping only 85 feet per mile southeast. Several northwest-trending folds occur, but they are broad and inconspicuous; the amplitude is not more than 13 feet. In places the middle salt marker shows undulations or crinkles that have an amplitude of about 6 inches. A characteristic feature of the middle salt marker is that its position changes more than 3 feet with respect to the upper marker bed, but these variations are independent of the gentle folds that affect all beds. They are believed to be a primary feature of the sedimentation, as discussed later.

No faults have been seen in the salts exposed in the International mine. Joints are present in the bodies of langbeinite, the most brittle mineral in the zone, but terminate above and below at the contact with halite or sylvite.


Typical section where langbeinite is predominant potassium mineral
Top of level
Salt clay
Sylvite. Usually absent where langbeinite is richest
Langbeinite. Often contains minor amounts of sylvite
Middle salt marker (orange halite with clay above and below)
Langbeinite. Has greater areal extent than langbeinite above middle salt marker
Top of lower salt marker (indistinct band of orange halite)
Halite
Bottom of level
Typical section where langbeinite has intermediate development
Sylvite. Upper 1 foot usually above 15 per cent K_2O
Mixed sylvite, langbeinite, and halite. Above 15 per cent K_2O as sylvite in places
Langbeinite
Middle salt marker
Langbeinite
Lower salt marker
Halite
Typical section where sylvite is predominant potassium mineral
Sylvite. Above 25 per cent K_2O where richest. Often contains minor amounts of disseminated langbeinite
Middle salt marker
Langbeinite most abundant below marker. Sylvite present but rarely attains grade of 15 per cent K_2O
Lower salt marker
Halite

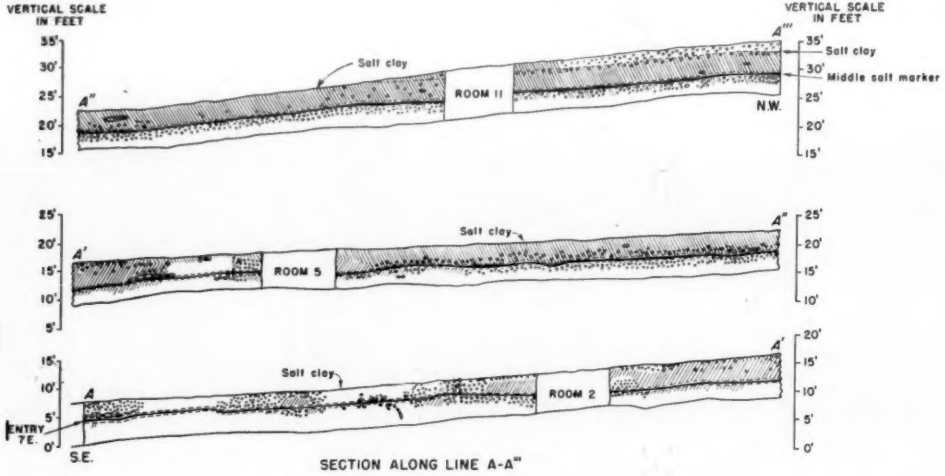
In each of the above sections the potassium minerals occur in a matrix of halite. Exposed sections average 7.3 feet in height.

TYPICAL STRATIGRAPHIC SECTIONS THROUGH POTASSIUM-BEARING BEDS

800 LEVEL

INTERNATIONAL MINERALS AND CHEMICAL CORPORATION, POTASH MINE
EDDY COUNTY, NEW MEXICO

Figure 1



SECTION ALONG LINE A-A'''

EXPLANATION

Halite

Langbeinite (and halite)
Diagonally ruled is + 8 per cent K_2O

Sylvite (and halite)
Diagonally ruled is + 15 per cent K_2O

Lens of pure halite

Lens of pure sylvite

Potassium minerals in middle salt marker omitted

Vertical scale exaggerated two and one half times horizontal scale

SECTION A-A''' ENTRY 8 NORTH
800 LEVEL
INTERNATIONAL MINERALS AND CHEMICAL CORPORATION, POTASH MINE
EDDY COUNTY, NEW MEXICO

25 0 25 50 75 100 FEET
HORIZONTAL SCALE

Figure 2

Relations of Potash Concentrations to Stratigraphy.—In the part of the level that has been studied the distance between the salt clay bed at the top of the level and the middle salt marker ranges from 2 feet to slightly more than 5 feet. Likewise, the distance between the middle salt marker and the lower salt marker changes, but this change is much smaller and must be measured in tenths of a foot. So far the distance between these beds has been systematically measured only in one small area where the lower salt marker is exceptionally distinct.

Variation of the distance between the salt clay bed and the middle salt marker is the result of a change in position of the salt marker, as shown by the fact that the salt clay bed has a relatively smooth profile. The variations are independent of the small folds due to tectonic movements; they are believed to result from irregularities on the floor of the evaporating pan at the time the middle salt marker bed was deposited.

The potassium minerals are concentrated where the distance between marker beds is greatest. Where the separation of marker beds is least, halite fills the space between them, and potassium minerals are present only in trace quantities if at all. This relation is remarkably persistent and, with the exception of a narrow strip in the western part of the level where the salt clay cannot be identified, holds true for all parts of the level that have been studied.

Masses of pure, clear, or nearly clear, coarse-grained halite occur in concentrations of potassium minerals and in fine-grained halite, but such masses of potash-free halite are only of local extent. Most of them are very coarse grained, and are entirely free of admixed clay and silt, which normally occur in all of the salts; they cut across beds of clay and across the marker beds. The clay that was originally distributed through the areas now occupied by these masses is concentrated as a selvage along the lower side. The halite masses are regarded as being later than the enclosing salts principally because they replace marker beds, and because of their coarser texture and lack of clay. Unfortunately, no examples that replace stratigraphic markers are present in section A-A‴, Figure 2.

The distance between the salt clay bed and the middle salt marker is shown by isopachs on Figure 3; the thicknesses of the langbeinite concentrations and the sylvite concentrations are shown by isopachs on Figure 4. The isopachs, both on Figure 3 and on Figure 4, are based on measurements made at 384 stations in the mapped area that have an average spacing of less than 25 feet. Isopachs of the concentrations of langbeinite and of sylvite are based on estimates of grade of the two minerals made at each station. The critical grades, 8 percent K_2O equivalent for langbeinite and 15 percent K_2O equivalent for sylvite, were selected because they represent the lowest concentrations of the two salts that are mined at the present time. The grade of langbeinite bodies can be estimated very closely because of the greater hardness and lack of cleavage of this mineral; less accuracy can be claimed for the estimated grade of sylvite because sylvite does not contrast so sharply with admixed halite. Skill in estimating the grade of langbeinite and sylvite was developed by comparing analyses with walls from which the samples had been taken. Analyses of samples taken at numerous places in the workings served as a check on esti-

Base map copied from mine map of International Minerals and Chemical Corporation

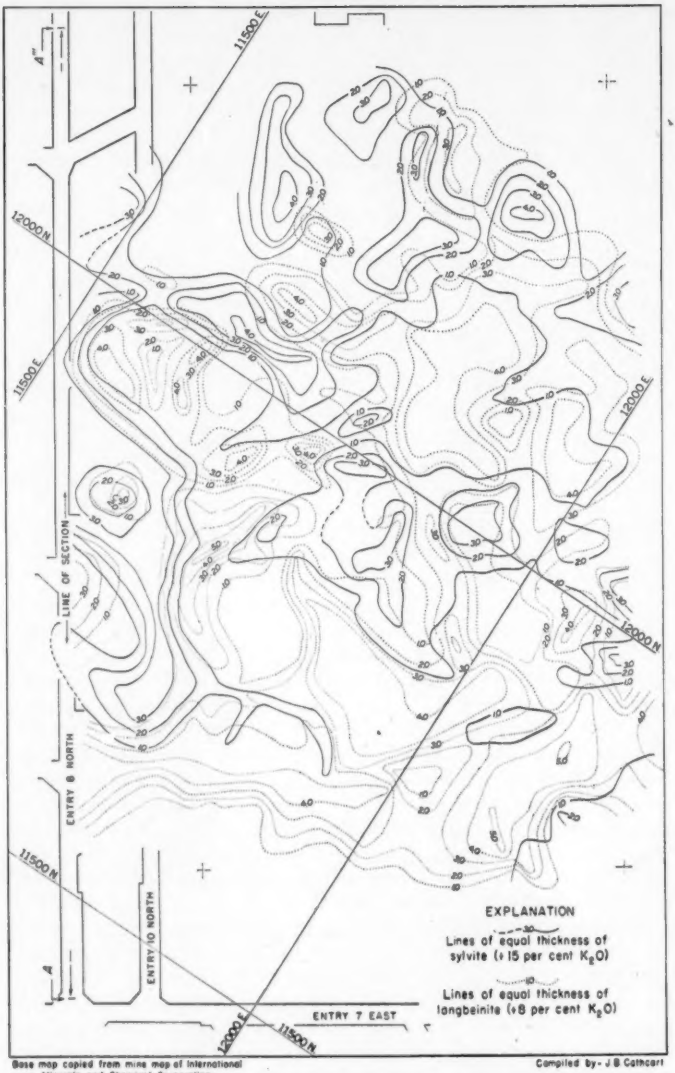
Geology by John C. Dunlap and Chao Chia-Hsiang

ISOPACH MAP OF DISTANCE BETWEEN MIDDLE SALT MARKER AND SALT CLAY
800 LEVEL
INTERNATIONAL MINERALS AND CHEMICAL CORPORATION, POTASH MINE
EDDY COUNTY, NEW MEXICO

50 0 50 100 150 200 FEET

ISOPACH INTERVAL 0.5 FEET

Figure 3



Base map copied from mine map of International Minerals and Chemical Corporation

Compiled by - J B Cathcart

ISOPACH MAP OF LANGBEINITE AND OF SYLVITE CONCENTRATIONS
800 LEVEL
INTERNATIONAL MINERALS AND CHEMICAL CORPORATION, POTASH MINE
EDDY COUNTY, NEW MEXICO

50 0 50 100 150 200 FEET

ISOPACH INTERVAL 1.0 FOOT

Figure 4

mated grades; therefore it is thought that the overall picture of the concentrations would not be changed significantly by analyzing samples from each station. Difficult accessibility caused by the large volume of waste material stored in the old workings plus the time required for collecting and analyzing samples combine to make sampling at each station impractical.

For convenience in comparing isopachs on Figure 3 with those on Figure 4, langbeinite concentrations and sylvite concentrations below the middle salt marker are ignored in order that the same stratigraphic interval may be compared. Zip-a-tone patterns are used on Figure 3 in order to define more clearly the areas in which the distance between the salt clay and the middle salt marker is greatest and in which the concentrations of potassium salts are thickest.

Vertical Distribution of Potassium Minerals.—Where langbeinite is best developed it, with admixed halite, completely fills the stratigraphic interval between the salt clay bed and the top of the lower salt marker. Thus, in the area covered by Figure 4, the interval that contains 8 percent or more K_2O as langbeinite (35 percent langbeinite, 65 percent or less halite) has a maximum thickness of slightly more than 7 feet, although a maximum thickness of only 5 feet is shown on Figure 4 as a result of eliminating langbeinite below the middle salt marker. Scattered blebs of sylvite accompany the langbeinite, and in most places where langbeinite has slightly less than the maximum thickness a thin layer of sylvite overlies it. These relations are shown graphically in the longitudinal section along Entry 8 North and in the left-hand columnar section on Figure 1.

Where langbeinite is intermediate in proportion sylvite is more abundant and occurs principally above the langbeinite. In such areas, sylvite is generally the only potassium mineral in the upper 1 foot of the wall; below this is a mixture of halite, sylvite, and langbeinite, which in turn is underlain by a concentration of langbeinite that contains only scattered blebs of sylvite. This concentration of langbeinite generally extends downward to the top of the lower salt marker; langbeinite between the two salt markers generally has greater areal extent than that above the middle salt marker. These relations, also, are shown graphically on the longitudinal section and in the center columnar section on Figure 1.

Sylvite is the predominant potash mineral at many places on the 800 level; it is most abundant in the northwest half of the area shown on Figure 4. In such areas sylvite is richest between the salt clay bed and the middle salt marker, the same stratigraphic interval that in adjacent parts of the mine contains most of the langbeinite. Where sylvite is most concentrated the deposit between the salt clay bed and the middle salt marker contains nearly 30 percent K_2O equivalent; therefore nearly half of the material is sylvite. Blebs of langbeinite occur throughout the sylvite but are more abundant in the lower half of the interval between the salt clay bed and the middle salt marker. Rarely, small areas between the salt markers contain sylvite equivalent to 15 percent K_2O. In sylvite-rich areas langbeinite is most abundant between the salt markers, and locally the concentration exceeds 8 percent K_2O equivalent.

Horizontal Distribution of Potassium Minerals.—As shown by the longitudinal section and by the isopachs on Figure 4, langbeinite is the dominant potassium mineral at some places and sylvite at others, both minerals occurring principally between the salt clay bed and the middle salt marker. Many lateral transitions from one of these minerals to the other and from concentrations of one of the potassium minerals to halite are abrupt, as shown, for example, on opposite sides of Room 5 on section A-A'''. At such boundaries the interface between the two mineral concentrations is not marked by any recognizable stratigraphic or structural feature; it is simply a change, gradual or abrupt, from one mineral concentration to the other.

A very characteristic feature of the langbeinite bodies is that their upper surfaces have the shape of the curved surface of a plano-convex lens. The best example of this feature in the area covered by Figure 3 is the remaining part of the langbeinite body in the wall of Entry 8 North on the northwest side of Room 5, shown in section A-A'''. A less distinct example on the same section is the body of langbeinite penetrated by Room 2. The example on the northwest side of Room 5 is typical of most rich bodies of langbeinite; where langbeinite is lean the upper surface is obscure.

Sylvite is the predominant potassium mineral in an area of considerable size northwest of the area mapped, and is most abundant in the northwest half of the area shown in Figure 4. It is common in a narrow area that corresponds roughly to the position of the 12,000 N grid line. In the area shown in Figure 4, sylvite generally is most abundant where the interval between the salt clay bed and the middle salt marker is less than 4 feet thick, and langbeinite generally is predominant where this interval is more than 4 feet thick.

SUGGESTIONS AS TO ORIGIN.

The writer believes that the variation of distance between the salt clay and the middle salt marker, the two beds that approximately represent the upper and lower limits of the principal concentrations of potassium minerals on the 800 level, is a primary feature of the sedimentation. This belief is founded on repeated observations that the variation of distance between these marker beds is entirely independent of small folds caused by tectonic movements and is always the result of relative change in position of the middle salt marker, the salt clay having a fairly smooth profile. According to the writer's interpretation, areas in which the middle salt marker is locally structurally low represent the site of small basins that existed on the floor of the evaporating pan at this stage of salt deposition. Conversely, areas in which the middle salt marker is locally structurally high represent the site of eminences on the floor of the evaporating pan.

As the concentrations of langbeinite and of sylvite occupy areas in which the middle salt marker is locally structurally low the interpretation is made that the potash salts were precipitated in small open basins at the top of the accumulating salt body and were later covered by succeeding layers of salt or were precipitated later from potash-rich brines that were trapped in porous

masses of halite in the basins and were unable to move freely through the halite. Whether or not the potash salts were precipitated directly from brines in open basins or came out of solution after being buried in porous, but impermeable halite is a difficult problem that has not been satisfactorily solved. Additional microscopic study of the paragenetic relations of the different saline minerals will be necessary before a firm opinion can be reached. By referring to section A-A''' it can be seen that concentrations of langbeinite and sylvite of the different grades mapped and halite without significant amounts of potassium minerals occur at the same stratigraphic level both above and below the middle salt marker. This distribution indicates to the writer that the various salts were either initially precipitated in the areas they now occupy or were deposited after burial from potash-rich brines that were trapped in the areas now occupied by the potash concentrations. The distribution of the potash concentrations does not favor the possibility of potash-rich brines being able to move freely through a porous mass of salt and attain stratified equilibrium as a result of differences in gravity. The only additional explanation of the erratic distribution of the concentrations of potash minerals that occurs to the writer would be leaching of the potash salts and reprecipitation in the pattern shown in section A-A''', but this possibility is thought to be very unlikely because no evidence was found for more than local solution and recrystallization such as that represented by the clay-free, very coarse grained lenses of halite, and by local lenses of polyhalite that occur outside of the area shown in Figure 3.

No definite explanation can yet be given for the areal distribution of langbeinite and sylvite, but according to the writer's interpretation the irregularities on the floor of the evaporating pan probably resulted in some segregation of brines of different richness and caused variation in currents and in temperature, factors that might cause precipitation of sylvite (or carnallite, if sylvite proves to be secondary after carnallite) rather than langbeinite.

USE OF GEOLOGY IN EXPLORATION AND DEVELOPMENT.

In that part of the 800 level shown in Figure 3 no definite pattern can be ascribed to areas where the distance between the salt clay and the middle salt marker is great. A similar study of a larger area may show some distinctive pattern that can be used as a guide in development. Continuation of the studies with this as one of the objectives seems to be the only possibility of establishing a geologic guide for locating the relatively small bodies of langbeinite ore. The presence of langbeinite deposits in the subsurface was, of course, first established by core-test holes, but excessive cost makes it impractical to attempt a detailed definition of the ore bodies by this method. Since development of the 800 level began, the method of exploration used has consisted in extending the regular pattern of main haulageways at reduced width until a body, or bodies, of langbeinite ore are encountered; the direction of haulageways is controlled by data from core-test holes. Unless additional detailed geologic studies of the kind described in this report demonstrate a pattern of distribution

of bodies of langbeinite ore, the described method of exploration will be relied upon in the future as in the past.

SUMMARY.

Detailed geologic studies on the 800 level of the International Minerals and Chemical Corporation's potash mine have shown that a definite relationship exists between the separation of stratigraphic marker beds and concentrations of potassium minerals in the Salado formation. The potassium minerals, chiefly langbeinite and sylvite, are most concentrated where the two most distinct marker beds are farthest apart and are absent or occur only in trace quantities where the beds are close together.

Langbeinite and sylvite occur in the same stratigraphic interval in adjacent parts of the mine; the change from one mineral concentration to the other is in many places abrupt and the interface is not marked by any discernible stratigraphic or structural feature. Blebs of sylvite occur throughout the langbeinite concentrations, but where the two minerals are present in quantity at the same locality sylvite is more abundant above the langbeinite. The upper surfaces of the langbeinite concentrations characteristically have the shape of the curved surface of a plano-convex lens.

The writer believes that the variation of distance between the salt clay and the middle salt marker beds is a primary feature of the sedimentation. This belief is supported by the fact that variation of distance between these marker beds is independent of small folds caused by tectonic movements and is always the result of relative change in position of the middle salt marker. As a result of this belief the interpretation is made that areas in which the middle salt marker is locally structurally low represent the sites of small basins that existed on the floor of the evaporating pan at this stage of salt deposition, and the converse, that areas in which the middle salt marker is locally structurally high represent the former sites of eminences on the floor of the evaporating pan.

Because the concentrations of langbeinite and of sylvite occupy areas in which the middle salt marker is locally structurally low the interpretation is made that the potash salts were precipitated in small open basins at the top of the accumulating salt body and were subsequently covered by succeeding layers of salt, or were precipitated after burial from potash-rich brines that were trapped in porous but impermeable halite in the basins. A more precise determination of the time of precipitation of the potash salts is not possible until the paragenetic relations of the individual minerals are investigated further, but the writer favors the first possibility because of his belief that variations in temperature were important and were greater in the open basins. The clay-free, coarse-grained halite that occurs in masses that cut across and replace stratigraphic markers is the only mineral seen in the area covered by this report that megascopic evidence indicates to be later than associated minerals.

The studies described in this report have not disclosed a pattern of distribution of langbeinite ore bodies that can be used in planning exploitation of the ore. The writer believes, however, that continuation of similar studies

offers the only hope of obtaining a geologic guide to the distribution of the ore bodies.

U. S. GEOOGICAL SURVEY,
WASHINGTON, D. C.,
July 10, 1951.

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5. Lang, W. B., Geology of the Pecos River between Laguna Grande de La Sal and Pierce Canyon: New Mexico State Engineer 12th and 13th Bienn. Rept., p. 84, 1938.

DISCUSSIONS

Sir: Dr. Alan M. Bateman's review of Dr. Tromp's book, "Psychical Physics—A Scientific Analysis of Dowsing, Radiestesia and Kindred Divining Phenomena" has been read with great interest. All too frequently scientists, and particularly some university professors of physics, tend to treat with scorn and ridicule the work of serious and honest, but possibly less erudite, investigators of such psychic phenomena.

Is it not time that such gentlemen instead of condemning dowsers as rogues and charlatans should really make a serious study of their work and methods? It is no longer good enough to merely state that dowsers as a body are not to be trusted and that where they are successful in locating water or minerals it is due to chance or to their having some prior knowledge of local conditions. Far too many cases are known of honest, but generally humble, men and women successfully locating sites for wells and finding mineral veins for anyone to deny that some persons have the ability to divine successfully.

In many instances known to the writer the dowsers have not worked for fees or wages but merely to oblige friends and in some cases they were not anxious to make public demonstrations of their ability.

Dr. Thwaites in his letter (ECON. GEOL., vol. 46, no. 3, p. 431) seems very concerned in case Dr. Bateman's review of Tromp's book should leave the reader with the impression that he may "endorse the claims of users of the ancient divining rod which has many modern varieties" and Dr. Bateman can best declare whether such was his intention, but if it was, is there any good reason why he should not do so?

Rogues and charlatans there are but do not let us condemn every dowser for the sake of certain dishonest men.

The writer with only a limited knowledge of some of the mysteries of divining can refute Dr. Thwaites' statement that dowsers—"get no response from the object of search until they are directly above it regardless of depth."

That statement first of all implies that dowsers *do* get results but only when they pass directly over the object for which they are dowsing. He might agree also that since the object is hidden from everyone's sight below the surface of the earth and if no one but the dowser can determine its location, even when only standing directly over it, then he is performing a useful service which others seemingly have not the natural ability to perform.

Secondly, the writer can testify that dowsers can, and do, obtain reactions when approaching a lode or an object but the violence of the reaction is at its maximum when the dowser is directly over it. One might reasonably expect this to be the case, for as Dr. Thwaites himself has stated, the intensity of electromagnetic waves decreases away from the source according to the square of the distance.

The writer unfortunately has not been able to obtain a copy of Dr. Tromp's book so is not in a position to comment on any of the statements made therein but he wishes to express his pleasure that someone has devoted so much of his spare time to recording little known facts in this field of psychical phenomena and for carrying out useful research work despite the unreasonable attitude of those who are content to scoff at the results and reports of a few men who in most cases are honest researchers anxious to find the answers to many things which we know are part of our experience but which are sometimes quite impossible to explain in scientific terms.

J. C. DAVEY.

SAFAGA,
UPPER EGYPT,
August 30, 1951.

REVIEWS

Refractory Clays of the Maryland Coal Measures. By KARL M. WAAGÉ. Pp. 182; figs. 26; pls. 8; tbls. 2. Maryland Dept. Geol., Mines and Water Resources Bull. 9, Baltimore, 1950.

As is pointed out in the preface of this bulletin, coal and refractory clay are the two most important mineral products of Western Maryland. At two previous periods, 1902 and 1922, the Maryland Geological Survey has made parallel studies of these two resources, and this bulletin is one of the products of the latest study. An extensive diamond drilling program of the coal measures by the U. S. Bureau of Mines has furnished fundamental data both for the study of the coal deposits and for this detailed study of the underclays by the U. S. Geological Survey in cooperation with the Maryland Department of Geology, Mines, and Water Resources.

The author has taken full advantage of the opportunity afforded by sixty-six diamond drill holes totaling 47,533 feet and a modern topographic map of the Castleman basin to make an important contribution to the geology of the Maryland refractory clay deposits. He points out that "efficient exploration for clay deposits requires (1) a thorough geologic study of the character and distribution of rock formations that are likely to contain clay beds and (2) the systematic prospecting of these formations." In Part I he fulfills the first requirement with respect to the clay bearing portion of the Maryland coal measures in general. Part II is concerned with the Castleman basin, the clay deposits of which have only recently been exploited on a large scale and are consequently less well known than those of the Georges creek basin.

Stratigraphy is of fundamental importance to the prospecting for clay deposits and their evaluation. In this report the stratigraphy of that part of the Carboniferous from the base of the Pottsville to the base of the Upper Conemaugh is treated in detail with very effective use of many page size graphic sections and correlation charts within the text. The scale of the figures varies with detail to be shown. The full logs of the holes in the Georges creek basin have already been published elsewhere by the Bureau of Mines [1] and those of the Castleman basin will doubtless be published in the future.

Due to the absence of fossiliferous marine beds, correlations are made chiefly by comparing lithologic sequences. The concept of the cyclothem is accepted and the relationship of the clays to the cyclothem discussed.

The six principal zones containing the high-alumina types are limited to the Allegheny formation and the lower part of the Conemaugh formation. Each zone is described in detail and evaluated. The Mount Savage clay deposits have furnished most of the refractory grade flint clay and much of the soft clay of Maryland. The Lower Kittanning clay is also worked and the Middle Kittanning furnishes soft clay for one plant.

[1] Toenges, Albert L., et al.: Investigation of the Lower coal beds in Georges creek and north part of upper Potomac basins, Allegany and Garrett counties, Md.: U. S. Bur. Mines Tech. Paper 725, 1949.

Apparently an erroneous belief that the Mount Savage clay is a relatively persistent bed of fairly uniform high grade has made detailed prospecting seem unnecessary in the past. Dr. Waagé gives convincing evidence of the irregular, lenticular character of the clay bodies. The Lower Kittanning clay is more regular but of lower grade than the Mount Savage clay. The Bolivar clay is not workable in the Georges creek basin but Dr. Waagé considers it, next to the Mount Savage, the most promising in the Castleman basin for high grade deposits of flint clay. He concludes that the reserves of known high grade clay deposits are insufficient to maintain production of firebricks to the capacity of the three plants and that detailed prospecting will be required to delimit the known clay bodies and to explore for new ones.

The mineralogy and petrography of the clay deposits are discussed only in a general way. Sixty-five ultimate analyses and fusion points are given in the appendix but a detailed discussion of the chemical characteristics of the clay is not within the scope of the report.

A geologic map on the scale of 1/24,000 shows the principal formations, the traces of prominent coal beds and the U. S. Bureau of Mines drill holes in the Castleman basin. The reviewer wonders why structure contours were not also shown.

The binding and typography maintain the high standard for which the Maryland Geological Survey is well known. This bulletin is a credit to the author and to all three organizations which have had a part in the project. It is to be hoped that some other publication will cover in more detail some phases of the refractory clays which are only briefly touched upon here, such as the mineralogy, chemical characteristics and the origin of the various types. In the meantime this report should be invaluable to any company trying to solve the most important problem of increasing the reserves of refractory clay.

JOE WEBB PEOPLES.

WESLEYAN UNIVERSITY,
MIDDLETOWN, CONN.,
Sept. 21, 1951.

Die Lagerstätte der Trepča und ihre Umgebung (The Trepča Ore Deposit and its Environs). By PROF. DR. ING. F. SCHUMACHER. Pp. 65; figs. 6; pls. 14, including 2 colored geologic maps, scales 1:20,000 and 1:5,000. Published by Izdavačko Preduzeće Sareta za Energetiku i Ekstraktirnu Industriju Vlade Fnrj, Beograd, 1950. German and Serbian editions with pasteboard cover. Price, 150 Dinars. German edition, F. Schumacher, Spaichingen/Württbg., Postfach 41, Westdeutschland. Price, DM 10.—

Dr. Schumacher left the Freiberg School of Mines soon after the close of World War II to become geologist at the then nationalized Trepca mines in Yugoslavia. The manuscript was completed at the mines at Stari Trg by the end of 1948.

The Trepca mine was developed into one of the world's great lead-zinc producers so recently that little or no account of this remarkable ore body is found in most text books on ore deposits. Schumacher characterizes it as an outstanding example of a high temperature metasomatic lead-zinc deposit genetically related to a young volcanic eruption. He calls it a counterpart of Leadville, Colorado.

Schumacher's description of the deposit is largely an amplification of the description by Charles B. Forgan in Mining and Metallurgy in 1936 supplemented by geo-

logic maps and sections made by Forgan as chief geologist of the Trepca Mines when they were operated by the Selection Trust. All of the illustrations and the two geologic maps are after Forgan without clear indication whether modified or supplemented by Schumacher. The bibliography cites five papers in Slavic published in not generally available Slavic journals dealing with mineralogic and petrographic features of the district, observations that are incorporated in Schumacher's account. Nevertheless, an abundance of new descriptive matter and statistical data is given, which together with the previously unpublished geologic maps and geologic sections of mine levels of Forgan makes this a valuable contribution to the literature on ore deposits. On the other hand, because of the economic importance and the geologic uniqueness of the deposit, it is unfortunate that the interpretations and conclusions are based on and supported almost entirely by general and megascopic observations and not on more exact and microscopic data.

The Trepca deposit appears to be by far the most important deposit in a large area in which mineralization occurs at many points and in which area extensive mining operations were carried on as early as Roman times and as late as the Fourteenth and Sixteenth centuries. The area was brought to the attention of the Selection Trust in 1925. After investigation, production was started in 1930 on a scale of 500 tons per day and expanded in 1936 to 1,600 tons per day.

A basement complex of supposedly early Paleozoic age consists of phyllites in which are included quartzite and limestone and minor intrusions of highly metamorphosed dolerite and serpentine. Over most of the area the basement rocks are covered by late Tertiary lavas and tuffs. A tightly folded anticline of limestone overlain by phyllite pitches northwesterly at an angle of about 37°. Along the contact of the phyllite and limestone at the top of the anticline is a core of volcanic rock surrounded by a breccia made up of fragments of the basement rocks and of the volcanic rocks in a matrix of finely divided materials of the same sort. Both Forgan and Schumacher consider it an explosion breccia filling an offshoot from a larger vent that forced its way along the broken crest of the anticline. The ore occurs in the limestone against the breccia on top and against the phyllite on both sides for some distance away from the breccia. Occasional ore masses are in the limestone a short distance away from the contacts.

The ore body has been proven continuous from its outcrop at elevation 935 m to a depth of about 140 m. Curiously, Schumacher suggests one can assume, therefore, that it will reach to sea-level. The area of ore on the thirteen mine levels between the elevations 865 m and 375 m averages 7,700 square meters. Above the 610 m level the average area of ore is 6,270 meters and below 610 m the average area is 9,850 m.

The tonnage of ore mined and its tenor in silica, lead and zinc are given annually from 1930 to 1944, inclusive. The total is 7,198,470 tons averaging 3.7 oz. Ag, 8.8% Pb, and 6.0% Zn. There is also a gold content of less than 0.2 g per ton. Because of the coarse grain of the ore, lead concentrates contain 80% Pb, zinc concentrates 50% Zn despite an isomorphous admixture of 11% Fe, and pyrite concentrates 48% S. A rough calculation of the value of the production based on prices in the United States during those years is $1,000,000 gold, $16,000,000 silver, $63,000,000 lead, and $52,000,000 zinc, a total of $132,000,000, exclusive of the pyrite concentrates, in 14 years, or an average of the order of $10,000,000 per year. Evidently Schumacher was not permitted to disclose the production for the years after the property was nationalized.

In a discussion of variation of metal content with depth, Schumacher averages the tenor of the production in three periods:

Period	Years	Pb	Zn	Ag	Total Pb + Zn
First	1930–1935	9.7%	8.4%	3.7 oz.	18.1%
Second	1936–1940	8.7	5.3	3.9	14.0
Third	1941–1944	7.4	2.8	3.9	10.2

These figures he points out suggest a striking decrease in zinc content with depth in contrast to the usual increase in zinc with depth in lead-zinc deposits. He explains this as only an apparent reversal resulting from the distribution of the lead and zinc in the ore body. In the upper levels, the ore masses tend to be restricted to the breccia contact and the lead and zinc occur together. In the lower levels more of the ore masses occur away from the breccia contact, and the lead was deposited to a larger extent in the ore masses at the breccia contact and the zinc to a larger extent in the ore masses further away from the contact. As prior to 1944, the production came largely from the ore at the breccia contact, the tenor of the production indicates a decrease in zinc content with increasing depth that is not inherent in the deposit as a whole. To prove that the change in tenor during these periods does not indicate a decrease in zinc with increasing depth, he cites the tenor of the 1948 production as 7.12% Pb and 5.50% Zn. Schumacher also calls attention to a decrease in total metal content with increasing depth from 18% to 10%. This would appear also to be an apparent rather than real decrease. Schumacher himself points out that the mineralization above the 610 m level occupies an average area of 6,270 square meters, whereas below that level it is spread out over an average area of 9,850 m. Furthermore, with increasing efficiency in operation and increasing rate of production, mines commonly progressively lower the tenor of the material mined. The operations during the first period were with a 500-ton mill and during the later periods with a 1,600-ton mill. Another important factor that affects the tenor of ore mined is the price of metals. The product of the sum of the metal prices and the sum of the ore tenors of the two metals is almost exactly the same for the three periods. This constant is hardly a mere coincidence.

The principal ore minerals in order of decreasing abundance are pyrrhotite, pyrite, galena and sphalerite, and marcasite. Widespread but minor accessory ore minerals are arsenopyrite, pyrite, stibnite, bournonite, boulangerite, and plumosite. The accompanying gangue minerals are quartz and a variety of carbonates ranging in composition from calcite to dolomite, siderite, and rhodochrosite. Formed earlier than these minerals are the common contact metamorphic reaction silicates. Pyrite has extensively replaced pyrrhotite. Schumacher describes unusual examples of resulting pseudomorphism. Though the prevailing texture of the ore is coarse irregular granular, it is unusually drusy. Schumacher likens it to a sponge and describes quite fully the magnificent crystal formations in the druses. He ranks them as one of the outstanding mineral-collecting localities in the world.

Enveloping the ore bodies and extending beyond them into the limestone are masses of carbonates, more or less impregnated with the ore minerals but rarely abundant enough to constitute workable ores, which Schumacher describes as closely related but which are not very clearly differentiated by him, under the names of "mineralisierten karbonate" and "rhodochrositemittel." The latter he says contain an average of 30% Mn+Fe, which on roasting would be increased to 45%, and occur in sufficient quantity to be of potential value to the iron and steel industry.

That the mineralization is genetically related to the late Tertiary igneous activity of the area is convincingly demonstrated. That an earlier stage of pyrometasomatism barren of the metals was followed by a later hydrothermal stage accompanied by the metals and which decreased in temperature from a pyrrhotite facies to a pyrite facies is likewise established. That the ore solutions were dammed against the in vertical cross section roughly horseshoe-shaped barrier formed by the breccia pipe on the top and the phyllite on the sides of the limestone and deposited their mineral load by replacement of the limestone must be accepted. What the course of the solutions was from the magmatic source to the locus of deposition is not so clear. Schumacher believes that the pyrometasomatism of the limestone occurred prior to the penetration of the breccia neck. That the breccia includes pieces of skarn is not definitive proof because pieces of limestone might have been converted to skarn in the breccia pipe itself. Obviously the shattered crest of the anticline afforded a favorable course along the phyllite-limestone contact for the explosive escape of the pipe material. Schumacher believes the later hydrothermal ore-bearing solutions reached their destination by the same route. In that event, to deposit the ores the solutions must have moved downward into the limestone and downward along the phyllite-limestone contact away from the breccia-limestone contact at the top of the inverted trough. The relations of the various ore masses to the breccia-limestone contact as shown in the horizontal sections of the mine levels and the descriptions of the dead ends in which the maximum mineralization occurred suggests not that the breccia-limestone contact was a channel of access but was rather a dam that impeded the movement of solutions that were rising through more complex and more intricate channels in the basement rocks themselves. Schumacher describes the limestone as extensively and complexly fractured and emphasizes the occurrence of the ore body at the junction of two major tectonic lines—at the eastern edge of the northwest-trending Wardar thrust zone and a northward-trending branch through the Kopaonik Mountains. Many important lead-zinc deposits are located along both of these tectonic zones. Similar mineralizing solutions in the 1 to 2 km distant lead-zinc deposits of Meljenica and Mažić had no breccia contact on top of the limestone to serve as a channel but rose through the limestone along fractures. Lacking a dam to stagnate them at the top, they failed to deposit large bodies of concentrated ores. Schumacher, however, ascribes the failure to less copious quantities of solutions. It would seem more logical to regard the breccia-limestone contact in the Trepca deposit as the bottom of the inverted trough toward which the solutions converged and were held than as the channel along which they came from their magma source and from which they diverged downward into the limestone and along the phyllite-limestone contact.

JOSEPH T. SINGEWALD, JR.

THE JOHNS HOPKINS UNIVERSITY,
BALTIMORE 18, MD.,
Sept. 26, 1951.

Stratigraphie und Palaeontologie des Oolithischen Eisenerzlagers von Herznach und Seiner Umgebung. By A. JEANNET. Pp. 240; figs. 544; pls. 107. Hallwag AG., Bern, 1951.

Stratigraphy and Paleontology of the Oolitic Iron Ore Deposits of Herznach and its Surroundings is the fifth volume of a series entitled Iron and Manganese Ores of Switzerland. It was preceded by Pisolitic Ore, Hematite, Siderite and Manganese Ore (1923), The Swiss Iron Ore Industry, its History and Economic

Importance (1932), Petrographic Study of the Minerals of the Oolitic Iron Ore of the Swiss Alps (1945), and The Magnetite Deposits (1948).

The present volume should contribute to dispell the frequently misconceived notion that paleontology is far removed from economic geology. Although this volume is a predominantly paleontologic contribution the detailed study of the fossils of the Dogger will facilitate stratigraphic correlation, which is of practical value to the mining industry.

The stratigraphy is covered in five pages and includes varied interpretations of the Herznach section. 232 pages are devoted to paleontology. Except for one crustacean, the books deals exclusively with mollusks, viz. nautiloids, belemnites and ammonites, greatly detailed and painstakingly illustrated with line drawings. 107 plates, some with more than ten photographs, conclude this volume. Although it is a comprehensive treatise, this work is not complete. The giant perisphinctids, the cardioceratidae, as well as a number of other ammonite families have not been included in the present volume. However, the author has promised to make up for this deficiency in a later volume.

GERALD M. FRIEDMAN.

UNIVERSITY OF CINCINNATI,
CINCINNATI 21, OHIO,
Sept. 26, 1951.

Mineralogy—An Introduction to the Study of Minerals and Crystals, 4th Edit. By EDWARD HENRY KRAUS, WALTER FRED HUNT, AND LEWIS STEPHEN RAMSDELL. Pp. 664; figs. 735; tbls. 37. McGraw-Hill Book Co., Inc., New York, 1951. Price, $7.50.

The 4th editlon of this well known textbook, which first made its appearance in 1920, includes the significant advances that have been made in the field of mineralogy in the 15 years that have elapsed since the 3rd edition. This applies particularly to the knowledge of crystal structure and chemical composition of minerals because of advances in X-ray analyses. The book has been reset, the text matter modernized, the determinative tables revised and many new photographs and drawings included. The book should continue to hold the former position established by itself.

Southeast Asia. By E. H. G. DOBBY. Pp. 415; figs. 118. John Wiley & Sons, Inc., New York, 1951. Price, $5.00.

This is a different kind of geography that deals with an area much in peoples' thoughts these days. Its intention is to give "a picture of environmental conditions and human adaptations in Southeast Asia to provide the student with a basic text and at the same time to stimulate the sociologist, administrator, the politician, and the business man to see the relation of their work to the general field." It traces the challenge and response of man and environment in Malaya, Burma, Indonesia, Thailand, and the Philippines.

The book is in 3 parts. The first, in 5 chapters, gives details of the natural landscape, climate, vegetation, and soils in the different countries. The second part, in 16 chapters, deals with the human detaiis of each area, and the third part, in 4 chapters, ties together the social, agricultural, and industrial life, problems and prospects for the future. The text contains numerous paragraphs on mining and minerals, geology and geomorphology. The book is very timely and should be read by all persons interested in this region.

A Roman Book on Precious Stones. By SYDNEY H. BALL. Pp. 338. Gemological Institute of America, Los Angeles 5, Calif., 1951. Price, $6.75.

This was Sydney Ball's last work and his greatest. His later writings had dealt almost exclusively with gemstones and he had become recognized as the world's leading authority on this subject. The manuscript of this book, a life-time of research, had been submitted to the publisher just before his sudden death.

One cannot read the book without amazement at the extent of the knowledge of the author on the ancient lore of precious stones. In the first of 3 sections, 12 chapters deal with Pliny the Elder, geological sources of gems, the ancient commerce, value and mining of gemstones in Pliny's time; and such other items as false stones, uses, jewelry lapidaries, Pliny as a gem expert, authorities cited by him and identification of Pliny's precious stones with those of today. The second section, set off by yellow pages, is the author's modernized version of Philomen Holland's English translation (1601) of the 37th Book of a Natural Historie of the World, by C. Plinius Secundus, in the First Century. The author gives in marginal notes his interpretation of the mineral terms used by Pliny and lists the sources of Pliny's statements as credited to other authors. Section III contains Sydney Ball's commentary on Pliny's statements in Section II, giving the authors named, and ancient localities and minerals discussed based upon the author's present day knowledge of the subject.

The book, although reading in places a little too much like a catalogue, is one in which all students of minerals, historians, and libraries will be interested.

Lagerstättenlehre, Ein Kurzes Lehrbuch von den Bodenschätzen in der Erde. By W. PETRASCHECK AND W. E. PETRASCHECK. Wien, 1950.

Reviewed in Volume 46, No. 5, August 1951.

Our textbook on economic mineral deposits was considered by the reviewer of your periodical to give the impression of having been compiled from outdated books twenty-five years ago. So far as this criticism concerns the few references to later American and English literature, a certain measure of truth must be admitted, because during the first years after the war when we wrote the manuscript only a few American or English books of the last twelve years were available in Austria. Unfortunately the excellent symposium *Ore Deposits as Related to Structural Features* by Newhouse et al., or McKinstry's *Mining Geology*, or Bateman's *Economic Mineral Deposits*, and many other important books and papers were unknown to us then; nevertheless we did use some postwar volumes of some American periodicals. But so far as the critique concerns Europe, the reviewer apparently did not distinguish what is old and what is new. Our book contains as examples many descriptions of mineral deposits that have been recently discovered or exploited for the first time in Germany or in the countries under the occupation of the German army during World War II. Not a small part of it is based on original research work of the authors in Eastern European countries during the war. The relation between ore and paleogeography in the Permian copper slate basin of Germany was established during the war. Different studies on coal metamorphism and the tectonics of the salt deposits of the Alps, although reported briefly, are new and based on the investigations of the authors. Typical cross-sections and descriptions of ore deposits in the Sowjetunion were taken from a postwar Russian book. It seems that either the reviewer is not too familiar with the later European mining developments or he read the book rather superficially.

The reviewer also seems to have an impression of brevity of our textbook. We think there are already a sufficient number of large books in each branch of Economic Geology. A new generalized American book on Economic Geology devotes only 10 percent of its content to coal. This does not seem adequate to the scientific nor to the economic importance of coal.

Not always is the newest the best, especially for teaching purposes. We have intentionally passed by some modern theories, or did refer to them only because they are as yet more terminological than proved. We do not hold a low opinion about the geology of 25 years ago, and especially of American geology, as it contains results and ideas that are valid even now.

W. PETRASCHECK AND W. E. PETRASCHECK.

MONTANISTISCHEN HOCHSCHULE,
LEOBEN, AUSTRIA,
August 30, 1951.

Igneous and Metamorphic Petrology. By FRANCIS J. TURNER AND JEAN VERHOOGEN. Pp. 602; figs. 92; tbls. 31. McGraw-Hill Book Company, Inc., New York, 1951. Price, $9.00.

This is a real vigorous advanced treatment of metamorphic petrology with a lesser amount of igneous petrology. The book is intended for the use of advanced students, research workers, and teachers in petrology, and its field will probably be restricted to that small group. The approach is quantitative physiochemical, and phase diagrams abound.

Chapters 2 to 6 deal with igneous rocks and magmas, their classification, equilibrium, variations, and their crystallization. Chapters 7 to 14 are concerned with various volcanic and plutonic associations, along with one chapter on pegmatites, lamprophyres and nepheline syenites, and another on the environment, origin, and evolution of magmas. Chapters 18 to 21 are a reduced version of the authors' earlier work on the "Mineralogical and Structural Evolution of the Igneous Rocks" (Geol. Soc. America Mem. 30, 1948) along with 40 figures from the same source. In this, Professor Turner, as would be expected from his training, deals intensively with petrofabrics.

The book is a monumental piece of work that is bound to become the outstanding reference on this subject.

BOOKS RECEIVED.

CHARLES H. SMITH.

U. S. Geological Survey—Washington, D. C., 1950–1951.

Bull. 955–F. Quicksilver Deposits of the Bonanza-Nonpareil District, Douglas County, Oregon. R. E. BROWN AND A. C. WATERS. Pp. 26; pls. 9; figs. 4; tbl. 1. *Most of ore is localized in shear zones in sandstone just below a shale member.*

Bull. 969–E. Quicksilver Deposits of the Horse Heaven Mining District, Oregon. A. C. WATERS, RANDALL E. BROWN, ROBERT R. COMPTON, LLOYD W. STAPLES, GEORGE W. WALKER, AND HOWEL WILLIAMS. Pp. 44; figs. 2; pls. 17. *Most deposits occur in or near autobrecciated plugs of biotite rhyolite and rich shoots are found underneath a clay sheet.*

Bull. 973–A. Magnetic Exploration for Chromite. H. E. HAWKES. Pp. 21; figs. 2; tbls. 3. Price, 15 cts. *A summary of the problem of magnetic ex-*

ploration for chromite. General features of chromite deposits, including magnetic properties of chromite, described. Many examples of field surveys given. In majority of areas magnetic surveys were of no use in locating chromite bodies.

Bull. 977. Bibliography of North American Geology 1949. EMMA MERTINS THOM, MARJORIE HOOKER, AND RUTH REECE DUNAVEN. Pp. 273. Price, 55 cts.

Bull. 978–A. Magnesium-Mineral Resources of the Currant Creek District, Nevada. CHARLES J. VITALIANO. Pp. 25; figs. 6; pls. 8; tbls. 3. Price, 70 cts. *Magnesite occurs as nodules, as veins, or lenses, and as disseminated grains in masses of altered calcareous Currant tuff. Ascending hot-spring waters, rich in magnesia, formed magnesium silicate, dolomite, and nodular magnesite. Reserves of recoverable magnesite are small.*

Bull. 981–A. Geophysical Abstracts 114, January–March 1951. MARY C. RABBITT AND S. T. VESSELOWSKY. Pp. 54. Price, 25 cts. *Nos. 12514 to 12700.*

Circ. 111. Carnotite Deposits in the Carrizo Mountains Area, Navajo Indian Reservation, Apache County, Arizona, and San Juan County, New Mexico. W. L. STOKES. Pp. 5; pl. 1; tbl. 1. *Describes carnotite deposits of ground-water origin in Morrison formation.*

TEM–31. Forty-Niner, King Solomon Ridge, and West End Claims near Clancy, Jefferson County, Montana. M. R. KLEPPER. Pp. 3; fig. 1. *Radioactive material in pyritic veins and altered aplitic granite.*

TEM–96–A. Progress Report; Wamsutter (Red Desert) Area, Wyoming. Pp. 2. *Schroeckingerite in fault structures leached from radioactive lignite and precipitated under near-surface conditions.*

TEM–97–A. Progress Report; Colorado Front Range Area. Pp. 2. *Deposits occur only in pyrite-bearing veins in or near granite gneiss and are closely associated with altered and weakly radioactive bostonite dikes.*

TEM–183–A. Interim Report of Geologic Investigation, Lost Creek Schroeckingerite Deposits, Sweetwater County, Wyoming. L. R. PAGE. Pp. 3. *Deposits localized within lower Eocene or younger clays and associated with fault zones.*

U. S. Atomic Energy Commission—Oak Ridge, Tennessee, 1950–1951.

RMO–659. Reconaissance Examinations of Copper-Uranium Deposits West of the Colorado River. DONALD L. EVERHART. Pp. 18; pls. 2.

RMO–660. Happy Jack Mine, White Canyon, Utah. PHILIP H. DODD. Pp. 23; figs. 4; pls. 3. *Uranium mineralization in flat-lying sandstone, with some leaching from the outcrop.*

RMO–673. Preliminary Report on Some Uranium Deposits along the West Side of the San Rafael Swell, Emery County, Utah. MILLARD L. REYNER. Pp. 31; figs. 12; pl. 1. *Describes 12 deposits near base of Shinarump conglomerate. Bulk of uranium is in intimate association with asphalt, and appears to have been introduced laterally along bedding planes.*

RMO–674. Reconnaissance of Basin-Boulder-Clancey Area, Jefferson County, Montana. MILLARD L. REYNER. Pp. 12; pl. 1. *Summary of observations at 15 areas which showed significant radioactivity.*

RMO–677. Annie Laurie Prospect, Santa Cruz County, Arizona. ROBERT J. WRIGHT. Pp. 8; pl. 1. *Pitchblende in a sheared porphyritic flow.*

RMO–678. Free Enterprise Uranium Prospect, Jefferson County, Montana. ERNEST E. THURLOW AND MILLIARD L. REYNER. Pp. 12; figs. 2; pls. 2. *Surface waters have concentrated and reprecipitated uranium in secondary minerals.*

RMO–679. Reconnaissance of Certain Uranium Deposits in Arizona. ROBERT J. WRIGHT. Pp. 21; tbls. 3; pls. 2.

RMO–753. Reconnaissance of Henry Mountains Area, Wayne and Garfield Counties, Utah. E. V. REINHARDT. Pp. 7; pl. 1.

RMO–797. Annual Report for July 1, 1950 to June 30, 1951. PAUL F. KERR, T. P. ANDERSON, C. A. RASOR, R. J. PILL, P. K. HAMILTON, H. WRIGHT, AND W. J. COHEN. Pp. 86; figs. 19; tbls. 4; pls. 2. *7 papers on areas in Montana, Utah, Colorado, and Ontario.*

Important Gold-Silver Mines of Japan. ROBERT Y. GRANT. Pp. 118; figs. 22; pls. 4; tbls. 124. Natural Resources Section Rept. 144, General Headquarters, Supreme Commander for the Allied Powers, Tokyo, 1951. *16 mines are described under the headings: location and history, economic importance, geology, ore deposit, mining, milling, production, and costs. Much statistical information.*

Talc Deposits of Steatite Grade, Inyo County, California. BEN M. PAGE. Pp. 35; figs. 25; pls. 11. California Div. Mines Special Rept. 8, San Francisco, 1951. Price, 85 cts. *General geology and individual mines described. Steatization accomplished by hydrothermal solutions acting on limestone, dolomite, silica rock, and granite.*

Illinois Geological Survey—Urbana, 1951.

Circ. 172. Mineral Resource Research and Activities of the State Geological Survey, 1949–1950. M. M. LEIGHTON. Pp. 30; illustrations.

Rept. Inv. 155. An Integrated Geophysical and Geological Investigation of Aquifers in Glacial Drift near Champaign-Urbana, Illinois. JOHN W. FOSTER AND MERLYN B. BUHLE. Pp. 30; figs. 4. *Reprinted from Economic Geology, June–July 1951.*

Geologic Structures in Kansas. JOHN MARK JEWETT. Pp. 65; figs. 2; tbl. 1. Kansas Univ. Geol. Survey Bull. 90, Pt. 6, Lawrence, 1951. *Lists and defines 161 geologic structures, with brief discussion of some of them.*

Ground Water Investigations along Bogue Phalia between Symonds and Malvina, Bolivar County. TRACY WALLACE LUSK. Pp. 19; pls. 4. Mississippi Geol. Survey Bull. 72, University, 1951. *Study of permeability and ground water supply of alluvium adjacent to Bogue Phalia.*

Pennsylvania Topographic and Geologic Survey—Harrisburg, 1951.

Bull. G–26. The Pennsylvania Mill Creek Limestone in Pennsylvania. MINCHEN MING CHOW. Pp. 36; figs. 3; pls. 4; tbls. 2. *Includes detailed description of fauna. Concluded to be a brackish water limestone of Conemaugh age.*

Bull. W–10. Ground Water for Air Conditioning at Pittsburgh, Pennsylvania. D. W. VAN TUYL. Pp. 34; figs. 9; tbls. 9. *Describes present development of water supply, factors affecting it and methods of conserving it.*

Bull. M–34. Geology of the Leidy Gas Field and Adjacent Areas, Clinton County, Pennsylvania. JOHN R. EBRIGHT AND ALBERT I. INGHAM. Pp. 35; figs. 2; pls. 3. *Description of stratigraphy and structure, measured sections and two geologic maps with structure contours.*

Progress Rept. 138. Geologic Structures of the Northern Plateaus Region of Pennsylvania. A. I. INGHAM. *Structures outlined on map of scale 1″ = 6 miles.*

Occurrence of Oil and Gas in Northeast Texas. Edited by FRANK A. HERALD. Pp. 449; numerous illustrations. Texas Univ. Pub. 5116, Austin, 1951. Price, $10.00. *Detailed descriptions of 135 fields accompanied by many structure maps and sections.*

Bibliography and Index of Geology Exclusive of North America, Volume 15, 1950. MARIE SIEGRIST AND MARCIA LAKEMAN. Pp. 429. Geol. Soc. America, New York, 1951.

Sequoia National Park—A Geological Album. FRANÇOIS E. MATTHES; edited by FRITIOF FRYXELL. Pp. 136; figs. 124. University of California Press, Los Angeles and Berkeley, 1950. Price, $3.75. *124 photographs accompanied by interpretations are grouped under eleven sections to illustrate many geomorphic phenomena.*

The Incomparable Valley—A Geologic Interpretation of the Yosemite. FRANÇOIS E. MATTHES; edited by FRITIOF FRYXELL. Pp. 160; pls. 50; figs. 11. University of California Press, Los Angeles and Berkeley, 1950. Price, $3.75. *After describing the valley, its waterfalls and domes, Matthes traces its evolution to the present. Many excellent photographs are included.*

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59th Annual Report, Being Vol. LIX, Part VII, 1950. Geology of the Keith-Muskego Townships Area. V. K. PREST. Pp. 44; figs. 4; photos 11; maps 3, including 1 colored geologic map, scale 1″ = 1,000′. *Keewatin volcanics and sediments, Haileyburian (?) diorite and serpentinite, Algoman granitic rocks described. Some gold mineralization.*

Map 1951–2. Township of Ashmore, District of Thunder Bay, Ontario. H. C. HORWOOD. *Colored geological map, scale 1″ = 1,000′.*

Map 1951–3. Township of Balmer, District of Kenora (Patricia Portion), Ontario. E. O. CHISHOLM. *Colored geological map, scale 1″ = 1,000′.*

Quebec Department of Mines—Quebec, 1949–1951.

Annotated List of Publications of the Department of Mines of the Province of Quebec, 1883–1948. Pp. 45. *Mimeographed appendix brings list up to 1950.*

The Mining Industry of the Province of Quebec in 1949. Pp. 99; tbls. 38; fig. 1. *Report on activities in metals and nonmetals, with statistics.*

Geol. Rept. 47. Bachelor Lake Area, Abitibi-East County. W. W. LONGLEY. Pp. 38; fig. 1; pls. 4; colored map, scale 1″ = 1 mile. *Keewatin (?) volcanics and sediments intruded by granite and quartz porphyry accompanied by gold-bearing quartz veins.*

Tin 1950–1951—A Review of the World Tin Industry. Pp. 84; 9 appendices; charts 8. The International Tin Study Group, The Hague, 1951. Price, 75 cts. *Economics, production, consumption, and trade of tin and the influence of the Korean war are described.*

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Bull. 19. Fluvial Andalusite Deposits in the Marico District. D. P. VAN ROOYEN. Pp. 18; figs. 3; pl. 1. Price, 1 s. *General geology and mode of origin described. Estimated to contain 800,000 tons of over 50% andalusite.*

Bull. 20. Earthquakes in South Africa. L. J. KRIGE AND B. D. MAREE. Pp. 14; fig. 1. Price, 1 s. *Presents data collected from eleven earthquakes since 1938.*

Pakistan Geological Survey—Karachi, 1950.

Vol. II, Pt. 2. A Survey of Coal Resources of Pakistan. N. M. KHAN. Pp. 11; pls. 3. Price, As. –/4/–. *Main deposits are of Eocene age, many are lignites.*

Vol. III, Pt. 1. The Water Supply of Baluchistan. A. H. KAZMI. Pp. 105; figs. 16. Price, Rs. 2/6/–.

Vol. III, Pt. 2. Report of the Geological Survey of Pakistan from 15th August, 1947, to 31st December, 1949. D. CROOKSHANK. Pp. 59. Price, Re. –/10/–.

Société Météorologique de France—Paris.

Fasc. 1. Bibliographie Météorologique Internationale, 1949. Pp. 264.

Tome VII. Bibliographie Météorologique Internationale, 1939. Pp. 487.

Mem. 33. Expédition Antarctique Française, 1948–1949. R. JALU. Pp. 21; figs. 12; pls. 2. *Preliminary report of meteorological observations.*

Recherches Géologiques et Minières aux Iles Saint-Pierre et Miquelon. E. AUBERT DE LA RÜE. Pp. 75; pls. 18; colored geological map, scale 1:50,000. Office de la Recherche Scientifique Outre-Mer, Paris, 1951. *First detailed study of these islands. St. Pierre is exclusively volcanic, Langlade is sedimentary, and Miquelon is partly volcanic and partly igneous, with some metamorphic rocks. These rocks are described in detail. Iron, copper, diatomite, barite, and pyrophyllite are among the minerals found.*

Service des Mines de Madagascar—Paris, 1949.

Notice Explicative sur la Feuille Besalampy. VICTOR HOURCQ. Pp. 12.

Notice Explicative sur la Feuille Soalala. VICTOR HOURCQ. Pp. 19.

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Feuille Bebao. *Colored, scale 1/200,000.*

Rapports et Bilans des Exercices 1948 et 1949. Pp. 191. Comité Spécial du Katanga, Bruxelles, 1951. *General review of activities in 1948 and 1949.*

Recursos Minerais do Estado de Minas Gerais. M. PIMENTEL DE GODOY AND IPHYGENIO SOARES COELHO. Pp. 138. Minas Gerais Dept. Agriculture, Belo Horizonte, 1947. *Short descriptions of all mineral occurrences in Minas Gerais.*

Minas Gerais Instituto de Tecnologia Industrial—Belo Horizonte, 1949.

Avulso 9. Cronogeologia dos Pegmatitos Brasileiros. WILLER FLORÊNCIO. Pp. 22. *Age determinations on radioactive minerals from Brazilian pegmatites. Ages range from 72·42 to 1,252·87 million years.*

Avulso 10. Estudo Químico da Apatita de Araxá. L. MENICUCCI SOBRINHO. Pp. 15; fig. 1. *A chemical study of apatite from Araxá.*

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Actividades Petroleras, No. 55. Pp. 14. *Drilling, production, and refining statistics.*

Revista, Año I y II, No. 2. Pp. 177. *Information on mining and petroleum industries in 1950, including a description of Cerro Bolívar by Mack C. Lake.*

Breve Historia de la Ingenieria Española. Pp. 227; numerous illustrations. Editorial Dossat, S. A., Madrid, 1950. *Brief history of Spanish engineering, with individual chapters on aeronautical and agricultural engineering, public works, industry, military, mining and naval engineering, forestry, and telegraphs. The chapter on mining traces the history of the mining industry from early times, through the period of Roman domination to the present, and includes a section on Spanish mining in America.*

SCIENTIFIC NOTES AND NEWS

HEINRICH RIES, 1871–1951. A MEMORIAL.

Dr. Heinrich Ries, Professor Emeritus of Geology of Cornell University and for 35 years Associate Editor of Economic Geology, died suddenly at his home in Ithaca, New York, on April 11, 1951. Death came unexpectedly in the midst of many activities and just two days before he was to have been honored at a "Dr. Heinrich Ries Night" when he was to have received a bronze plaque from the Central New York Chapter of the American Foundrymen's Society of which he was honorary member and chairman of its sand division.

Born in Brooklyn, New York, on April 30, 1871, Dr. Ries received his early education partly in this country and partly in Europe. He was awarded the Ph.B. by Columbia University School of Mines in 1892, the A.M. in 1894, and the Ph.D. in 1896. After a year of study at the University of Berlin he joined the Geology Department at Cornell University where he remained for 41 years until his retirement in 1939. From his appointment as Instructor in Economic Geology in 1898 he was advanced to Assistant Professor in 1902, to Professor in 1906, and to Head of the Department in 1914, a position he held until 1937.

Dr. Ries was widely known through his many publications which included eight books and more than 200 technical papers and bulletins. Among his books was his widely used text on "Economic Geology" which went through seven editions, the first of which appeared in 1905 and the last in 1937. He was also senior author of a text on "Engineering Geology" which passed through five editions and author of a book on "Clays, Occurrence, Properties, and Uses" which was being prepared for the fourth edition at the time of his death. Dr. Ries was regarded as an authority on clays and foundry sands and most of his technical writings dealt with these important materials. Because of his knowledge of these materials, his services were much sought after by State Geological Surveys and he was thus employed in clay studies by the States of Michigan in 1898 and 1906, Maryland in 1900, New Jersey in 1901 and 1902, Texas in 1903, Wisconsin in 1904, Virginia in 1905, 1915, 1916, and 1922, and Kentucky in 1921. He was also employed by the Canadian Geological Survey in 1910 and 1914 and by the U. S. Geological Survey, as special agent from 1895 to 1901 and as Geologist in 1918. His later interest was given largely to foundry sands and he continued to direct the work in the sand laboratory, which he established at Cornell University in the early twenties, to the very day of his death.

Dr. Ries belonged to many professional and scientific societies. He was a charter and honorary member of the American Ceramic Society, honorary member of the American Foundrymen's Association, honorary life member of the Canadian Institute of Mining and Metallurgy and the American Association for the Advancement of Science, life fellow of the Geological Society of America and the American Geographical Society, life member of the American Institute of Mining and Metallurgical Engineers, fellow of the Mineralogical Society of America, and member of the British Ceramic Society, the Society of Economic Geologists, the American Association of Petroleum Geologists, the Seismological Society of

America, the Society of Economic Paleontologists and Mineralogists, and the National Geographic Society. He was an honorary member of the Kentucky Academy of Sciences and the Rochester Academy of Sciences and a member of such societies as Sigma Xi, Phi Kappa Phi, Sigma Gamma Epsilon, and Gamma Alpha.

Many honors came to Dr. Ries, among them election to the presidency of the American Ceramic Society in 1910 and to the Presidency of the Geological Society of America in 1929. He was also called upon to serve on many committees. Alfred University honored him by the honorary degree of Doctor of Science in 1945. The American Foundrymen's Association recognized his work by awarding him its Joseph S. Seaman Gold Metal in 1936 and by support of his research on foundry sands. He became chairman of the new sand division of the association in 1946 after serving as technical director to the organization's sand project since 1929.

His interest in travel and matters geological prompted him to attend the meetings and field trips of the International Geological Congress in Russia, France, Canada, and Mexico. Until the very end he was a regular attendant at most of the meetings of the geological and mining societies held in this country and spent much time in travel to and from committee meetings. In late years he received the greatest enjoyment from vacation trips to the Far West where he had the opportunity to visit with many of his former students and share with them trips to points of geologic interest. His many friends will miss these annual visits.

His first wife, Mrs. Millie Timmerman Ries, died in 1942. He remarried in 1948, but his second wife, Mrs. Adelyn Halsy Gregg Ries, passed away early in 1950. He is survived by two sons, Professor Victor H. Ries of Ohio State University, and Professor Donald T. Ries of Illinois State Normal University.

ALFRED L. ANDERSON.

DEPARTMENT OF GEOLOGY,
CORNELL UNIVERSITY,
ITHACA, N. Y.,
Oct. 9, 1951.

JOHN H. MOSES resigned as chief geologist of the Cerro de Pasco Corporation after sixteen years service in Peru and accepted a position with the Reynolds Mining Corporation with headquarters in Little Rock, Arkansas. W. C. LACY, formerly assistant chief geologist, succeeds him as chief geologist for the Cerro de Pasco Corporation, with headquarters at Oroya, Peru.

JAMES C. BRICE, Assistant Professor of Geology at Washington University in St. Louis, has been awarded a grant of $4,300 from the Fund for the Advancement of Education, a Ford Foundation division. The grant is for the purpose of studying the experimental programs in general education now being carried on by several large universities, with the object of applying these new ideas and methods to the teaching of geology in general education. The first semester will be spent at Harvard University.

The New Mexico Geological Society guided a tour from Albuquerque on October 11th of three hundred professional geologists from eleven states to study the geology of the south and west sides of the San Juan Basin, a region of interest for new sources of oil and gas.

JOSEPH B. ELIZONDO, who served for three years as geologist at Casapalca for the Cerro de Pasco Corporation, is a graduate student at Harvard University this year.

A. F. FREDERICKSON, Associate Professor of Geology at Washington University, has been given a Fulbright Award for research in Petrology and Geochemistry in Norway and as a consequence has taken leave from the University for the year. Since August he has been doing field work in classic Norwegian localities. His headquarters is at the University of Oslo.

The U. S. Geological Survey and the Minnesota Geological Survey has disclosed that seven extensive belts of high magnetic attraction which possibly indicate iron-bearing rock formations have been discovered in northern Minnesota. Seven additional maps based on the aeromagnetic survey of approximately 45,000 square miles in the northern half of the state were released.

RODGERS PEALE, consulting geologist of San Francisco, California, and ALFRED WANDKE, JR., of Southwestern Geological Services, Prescott, Arizona, visited a number of mining properties in Peru and Bolivia during the summer.

OLOF H. R. ODMAN, of the Geological Survey of Sweden, has come to the United States on a study trip sponsored by the Economic Cooperation Administration under its productivity and technical assistance program. Sweden, one of the principal current foreign sources of iron ore for United States defense industries, wishes to increase this source of the much-needed ore. Dr. Odman is studying newer methods of mining, modern prospecting methods, grading of ores and inventory methods.

ROBERT Y. GRANT has resigned as Chief, Mining and Geology Division, Natural Resources Section, General Headquarters, Supreme Commander for the Allied Powers, Tokyo, Japan, and has returned to Seattle.

JOHN DALY has resigned as Supervisor for General Geophysical Company in West Texas and New Mexico to open an office in Midland, Texas, for consulting in geophysics and geology. Prior to joining General Geophysical Company in 1950 Daly was in charge of seismograph work for Honolulu Oil Corporation in West Texas, New Mexico, Colorado, and Mississippi. Prior to that time he was associated with Shell Oil Company as geologist and seismologist.

The new officers of the Brazilian Geological Society for the term September 1951 to November 1952 are as follows: Prof. Octavio Barbosa, President; Prof. Othon Henry Leonardos, and Prof. Frederico Waldemar Lange, Vice Presidents; Prof. Rui Ribeiro Franco, Secretary; Prof. Alceu Fabio Barbosa, Treasurer; Prof. Josué Camargo Mendes, Director of Publications.

CHARLES W. MERRILL, chief of the Base Metals Branch, U. S. Bureau of Mines, was named assistant chief of the Minerals Division, of which LOWELL B. MOON is the chief. Succeeding him as chief of the Base Metals Branch is CHARLES H. JOHNSON.

WALDEMAR F. DIETRICH, heretofore chief of the Rare and Precious Metals Branch, U. S. Bureau of Mines, was named chief of the Ceramics and Fertilizer Materials Branch, while RICHARD H. MOTE succeeds him as chief of the Rare and Precious Metals Branch. HELENA M. MEYER was appointed assistant chief of the Base Metals Branch, the post vacated by Mr. Mote.

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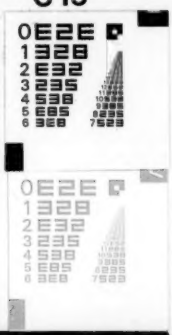
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